67th International Astronautical Congress (IAC), Guadalajara, Mexico, 26-30 September 2016.

IAC-16-C3.3.6

GOSSAMER Deployment Systems for Flexible Photovoltaics

Jan Thimo Grundmann[a]*, Peter Spietz[a], Patric Seefeldt[a], Tom Spröwitz[a]

[a] *DLR German Aerospace Center, Institute of Space Systems, Robert-Hooke-Strasse 7, D-28359 Bremen*, jan.grundmann@dlr.de
* Corresponding Author

Abstract

In recent years the German Aerospace Center (DLR) developed gossamer deployment systems in the GOSSAMER-1 project with a focus on solar sails also equipped with small thin-film photovoltaic arrays. With our new project GOSOLAR ahead, the focus is now entirely on gossamer deployment systems for huge thin-film photovoltaic arrays. Based on the previous achievements in the field of deployment technology and qualification strategies, new technology for the integration of thin-film photovoltaics will be developed and qualified with the goal of a first in-orbit technology demonstration. The time frame for this development is about five years. The two major objectives of the project are the further development of deployment technology for a 25 m² gossamer solar power generator and the development of a flexible photovoltaic membrane. In contrast to the GOSSAMER-1 deployment approach, GOSOLAR enables a wider range of deployment concepts. The technology demonstration is supposed to employ the S²TEP bus system which is developed on-site in parallel. While the development of a bus system is in consequence not part of the GOSOLAR project, there are special challenges when it comes to the development of huge solar arrays. The level of power required in the solar array application is about two orders of magnitude higher than for a sailcraft of the same size. The currents required to carry power off the thin-film structure at commonly used bus voltages result in a substantial harness cross-section. At the same time, there is a desire for higher voltages, e.g. to power electrical propulsion directly. In consequence the first system GOSOLAR will be a low voltage system employing off-the-shelf small spacecraft power system technology. The development of high power systems will be studied in parallel and its implementation is left to future projects. Using an established test strategy, a characterization of the deployment performance and deployment forces will be made based on a test-as-you-fly approach. It includes vibration testing, fast decompression, partial deployment under thermal-vacuum and full-scale ambient deployment on a test rig previously developed for GOSSAMER-1. The data gained can be used for further development and as input for mechanism and structure sizing. Examples for the application of those testing strategies are the previous DLR GOSSAMER-1 project, the ESA drag sail projects 'Deployable Membrane' and 'Architectural Design and Testing of a De-Orbiting Subsystem' (ADEO) as well as the tether deployment of the HP³ experiment on the NASA/JPL Mars mission INSIGHT.

Keywords: large-scale photovoltaics, thin-film photovoltaics, GoSolAr, S²TEP, GOSSAMER-1, solar sail

Nomenclature

(5 m)²	5 m by 5 m square deployed gossamer system
*npm*s	*n* units in parallel, *m* times in series
*nsm*p	*n* units in series, *m* times in parallel
V_{oc}	open-circuit voltage

Acronyms/Abbreviations

Architectural design and testing of a DE-Orbiting subsystem' (ADEO),
Air Mass *n* times Earth's atmosphere (AM*n*),
Battery Charge Regulator (BCR),
Boom Sail Deployment Unit (BSDU),
Copper Indium Gallium Selenide (CIGS),
Commercial Off-The-Shelf (COTS),
Collected Volatile Condensable Material (CVCM),
Deutsches Zentrum für Luft- und Raumfahrt – German Aerospace Center (DLR),
DLR Raumfahrtmanagement – Space Administration (DLR RM),
European Space Agency (ESA),
End-Of-Charge Voltage (EOCV),
End-Of-Discharge Voltage (EODV),
Electrical Power Subsystem (EPS),
Gossamer Solar Array (GOSOLAR),
Heat Flow and Physical Properties Package (HP³)
Jet Propulsion Laboratory (JPL),
Mobile Asteroid Surface scOuT (MASCOT),
Model-Based System Engineering (MBSE),
Miniature Module (MiMo),
Maximum Power Point Tracking (MPPT),
Maximum Power Point Tracking Battery Charge Regulator (MPPT-BCR)
National Aeronautics and Space Administration (NASA),
Product-Integrated PhotoVoltaics, here referring to the project Flexible CIGSe Dünnschichtsolarzellen für

die Raumfahrt – Flexible CIGSe Thin-Film Photovoltaic Cells for Spaceflight (PIPV),
PhotoVoltaic(s) (PV),
PhotoVoltaics eXperiment (PVX),
Recovered Mass Loss (RML),
Robotische Exploration unter Extrembedingungen - Robotic Exploration of Extreme Environments (ROBEX),
Qualification Model (QM),
Scanning Electron Microscope (SEM),
Single-Ended Primary-Inductor Converter (SEPIC),
Solar Array Normal to Sun angle (SAN2Sun),
Small Satellite Technology Platform (S^2TEP),
Standard Test Conditions (STC),
Solar Radiation Pressure (SRP),
Thermal-Vacuum (TVAC),
Zentrum für Sonnenenergie- und Wasserstoffforschung Baden-Würtemberg – Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW).

1. Introduction

The concept of sunlight as a practical source of energy goes back to Kepler's observations and remarks published in 1619 on the directionality of comets' tails relating to it a propulsive force [1]. This force was predicted to equal magnitude in 1873 by Maxwell on the basis of his electromagnetic theory [2] and in 1876 by Bartoli based on the Second Law of Thermodynamics [3] but could only be experimentally demonstrated as pressure due to radiation by Lebedev in 1901 [4] and by Nichols and Hull in 1903 [5].

In 1876 the discovery by Adams and Day of an electrical current driven by selenium exposed to light created the basis for solid-state electronics and a lightweight portable source of power that does not require a constant supply of fuel, water, or hard labour. Based on the same principle but refined by the knowledge of quantum mechanics, the silicon junction solar cell first serendipitously created in 1953 by Pearson, Chapin and Fuller at Bell Labs turned the photovoltaic effect from a sensor-level signal generator into a technically viable power source by 1956, although at first commercially restricted to the novelty toy and beach radio market.

Realizing the limits of chemical batteries in powering remote and expensive electronic experiments, Ziegler and Liderenko introduced photovoltaic cells on Vanguard-1 and Sputnik-3, respectively, where they successfully operated low-power optimized solid-state electronics for the entire orbital lifetime of either spacecraft.

Although then viewed as only an interim power generation method on the way from simple battery-powered missions using 'experimental' low-power devices such as transistors to complex long-duration nuclear-powered missions using proper vacuum tube based electronics, photovoltaic generators have become the prime power source in space [6] [7], relegating the others to niche applications mainly in exploration science missions. [8] [9] [10] [11] [12] [13] [14]

Kick-started by space applications, mass-produced photovoltaics have since become a commercially viable terrestrial power generator, expanding from small and remote locations to mains grid terrestrial applications.

1.1 Early Solar Sail Development at DLR

The development of solar sail technology has been ongoing at DLR for many years at varying levels of intensity. Practical design studies leading to full-scale experiments were undertaken since the 1990s. A first phase culminated in the successful ground deployment test of a (20 m)² boom-supported sail on December 17th, 1999. [15] This work was subsequently evolved over a decade in a continuous effort aiming at small-class science missions for exploration [16] [17] [18] [19] and geosciences [20] [21] [22].

1.2 The GOSSAMER Roadmap

In the wake of the GEOSAIL technical reference study [20][21][22] the previous work at DLR was extended into the framework of the DLR-ESTEC GOSSAMER Solar Sail Technology Roadmap in November 2009 by an agreement between DLR and ESA [23][24]. The technology demonstration mission based approach was chosen to separate the development of ultra-lightweight deployable structures from the paths, cycles and uncertainties of science-driven mission selection processes.

The GOSSAMER Roadmap consisted of three steps:

- GOSSAMER-1: low cost technology demonstrator for membrane deployment technology with a (5 m)² sail in very low Earth orbit (LEO).
- GOSSAMER-2: validation of solar sail attitude control technologies on a (20 m)² sail at altitudes where photonic pressure becomes dominant.
- GOSSAMER-3: fully functional (50 m)² solar sail to validate the design approach and prove sufficient guidance, navigation and attitude control to conduct planetary science and space weather missions.

The size and all other parameters of GOSSAMER-2 and -3 were only approximately defined based on parametric analysis on the background of GOSSAMER-1 design and construction experience, detailed design pending.

The following table lists the envisaged development and original point-of-departure configurations of the three spacecraft to be developed, at a point in time around the inception of the GOSSAMER Roadmap:

Table 1. The GOSSAMER Roadmap spacecraft

GOSSAMER	-1	-2	-3
deployed size	(5 m)²	(20 m)²	(50 m)²
deployed sailcraft mass	19.5 kg	57 kg *	~80 kg *
undeployed volume	Ø80·50 cm³	≤80·80·100 cm³	
sail foil	7.5 µm	2.5-7.5 µm	≤2.5 µm
mission objective	deploy ment	attitude control, orbit change	full orbit and attitude control
initial orbit	drag domi-nant	SRP domi-nant	spiral-up & -out feasible

* best estimate

It was envisaged to continue this line of development into small science missions which are uniquely enabled by solar sail propulsion.

The following three missions were identified and and studied over a period of two years:

- a spaceweather early warning mission stationkeeping with Earth ahead of the Sun-Earth Lagrange point L_1 towards the Sun, using the sail thust to augment Earth's gravity in the balance of orbital forces to generate an artificial Displaced L_1 point (DL1), and carrying a very lightweight suite of plasma instruments. The DL1 position was expected and required to at least double the warning time for oncoming solar storms which can disturb power grids, knock out spacecraft services, hinder radio communication, and increase high altitude radiation on Earth. Sail degradation during the mission would not lead to loss of stationkeeping, merely the displacement distance would recede in proportion back towards the purely ballistic L_1 region of halo orbits. [25]
- a Solar Polar Orbiter for which the solar sail is used to raise the inclination of its heliocentric orbit much further than possible by gravity-assist fly-bys, chemical or electrical propulsion combined. A heavier helioseismic imaging payload could be raised in inclination sufficiently to observe the polar regions of the Sun, and could progress under sail power to somewhat higher latitudes still withi the set lifetime. A light-weight plasma instruments payload could reach exact polar orbit within the required mission duration where the sail would be jettisoned to remove its influence on the plasma environment to be studied. The sail itself does however not run out of fuel to continue in either case, and could in theory be used for any useful minimal mass extended mission purpose progressing to retrograde inclinations. [26]
- a multiple NEO rendezvous and fly-by mission to visit and rendezvous for at least several rotation periods of the respective object with at least three significant NEAs of a pre-selected population and to perform fly-bys at additional other NEOs within the set lifetime of a decade. (Current analysis demonstrates at least 4800 target sequences, each visiting for of 100 days 5 NEAs out of a catalogue restricted to 1801 objects of 12840 NEAs in total, are accessible to such a first-generation sailcraft at 0.2 mm/s² characteristic acceleration in 10 years.) [27]

The requirements of all these missions can *only* be met using solar sail propulsion with a substantial margin to the second-best propulsion solution. Their requirements combined were intended to guide the Roadmap development towards GOSSAMER-3.

1.2.1 GOSSAMER-1

Within the framework of the DLR-ESTEC GOSSAMER Solar Sail Technology Roadmap, the German Aerospace Center (DLR) developed a gossamer deployment system in the GOSSAMER-1 project. Its focus was on solar sail propelled spacecraft based on the expected requirements of technology demonstration and initial small-scale science missions. It was anticipated that these were to be equipped with ultra-lightweight small – relative to the total sail area – thin-film photovoltaic arrays to power the mission.

We report on the GOSSAMER-1deployment technology experiment and demonstrator spacecraft design in detail in [28], [29], and references therein.

2. Photovoltaics in Space

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.

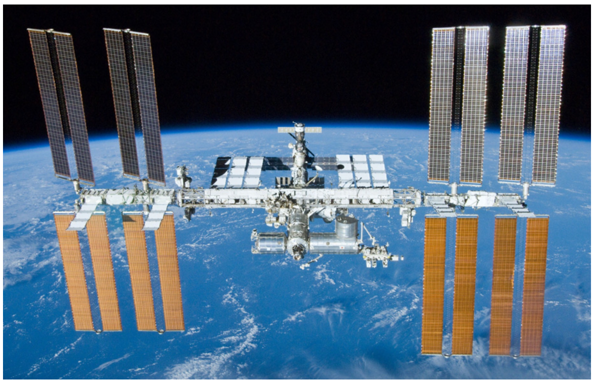

Fig. 1. ISS large-scale photovoltaics (NASA/Crew of STS-132).

Although not a high-power spacecraft, the Hubble Space Telescope provides an interesting study case regarding lightweight deployable solar panels since it was equipped at first with rigid photovoltaic cells mounted on a flexible substrate. Due to its extreme pointing accuracy and stability requirements, a minor jitter caused by thermal cycling of elements in the deployment mechanism was detected.

Fig. 2. Hubble Space Telescope flexible photovoltaics – (NASA / STS crews).

In later servicing missions, the flexible-substrate panels were eplaced by improved versions and finally by fully rigid panels providing higher pwer output despite being smaller, thanks to advances in PV cell technolgy achieved while the spacecraft was conducting its mission in orbit.

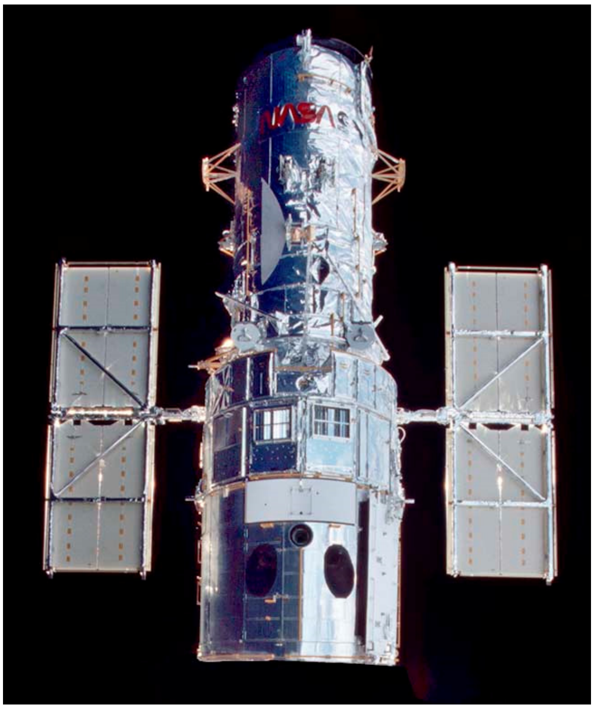

Fig. 3. Hubble Space Telescope rigid replacement photovoltaics – (NASA / STS crews).

However, the majority of high-power space applications as well as the largest deployables are on geostationary communication satellites. Currently, the PV design power of the largest spacecraft in this class approaches 20 kW. Antennae for mobile phone transponder payloads larger than 12 m in diameter have been successfully deployed and operated in space.

Fig. 4. Large deployable antenna main reflectors on geosynchronous communication satellites for direct-to-satellite mobile phone systems –Thuraya 2 and 3 design, 12.25 m antenna diameter (artists concept: Boeing BSS via Gunter's Space Page)

Fig. 5. Garuda-1 (ACeS-1) design, two times 12 m antenna diameter (Lockheed-Martin via Gunter's Space Page)

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. [30]

A thin-film photovoltaics experiment was part of the highly successful Japanese solar sail demonstrator IKAROS. [31] [32]

Predictions on the development of space technologies and applications expect continuing growth of energy demand in most spacecraft classes, particularly in the geostationary communication sector, small spacecraft services, and exploration missions. [33] Space applications with very high power demand are also found in planetary defense when it comes to the controlled deflection of asteroids. [34]

3. The GOSSAMER-1 Photovoltaic Experiment

The GOSSAMER-1 flexible thin film Photovoltaics Experiment (PVX) demonstrates the utilization of large, extremely lightweight deployable systems for solar power generation. If successful, the technology may see use in potential future solar sailcraft as main power generator as well as in other spacecraft where high power demand is the main driver, with weight reduction generally welcome in space applications.

The experiment focusses on thin film photovoltaic cells, mainly on polyimide foil as carrier substrate due to the materials compatibility and handling experience related to spaceflight. Such photovoltaic cells are highly compliant with the requirement of building flexible, deployable and light weight solar generators.

3.1 Spacecraft Overview

The design of the GOSSAMER-1 Deployment Demonstrator and the envisaged free-flyer spacecraft is presented in detail in [28] and [29]. The spacecraft consists of 5 sub-spacecraft. In the center is the actual sailcraft with a core section and the sail to be deployed. It is surrounded by 4 boom-sail deployment units (BSDU) which are jettisoned after sail deployment.

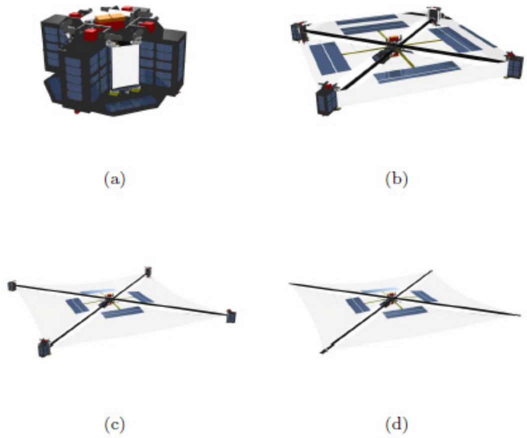

Fig. 6. Gossamer-1 deployment process, (a) launch configuration, (b) deployment, (c) deployed sail, (d) deployment mechanisms are jettisoned.

3.2 Power Subsystem Integration

Each of the five sub-spacecraft of GOSSAMER-1 contains an independent power subsystem. In the stowed configuration, power is generated by conventional rigid triple-junction PV cells on the outer panels of the sub-spacecraft, not unlike large cubesats. Each of them also has its own power distribution and a battery.

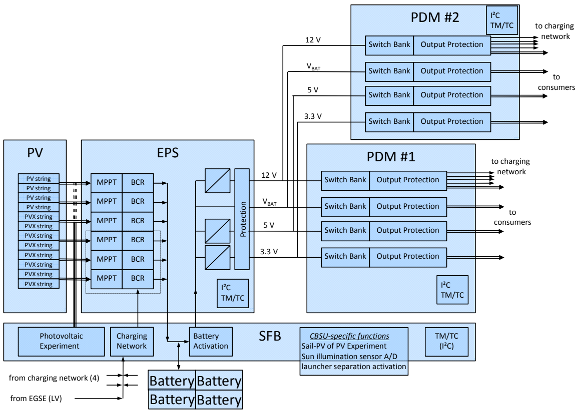

Fig. 7. Integration of the Photovoltaics Experiment into an off-the shelf power subsystem.

Since regular and continuous insolation can not be guaranteed after separation from the launch vehicle, a power sharing mechanism has been implemented which can transfer power to and from each BSDU via the core spacecraft. Any of the five sub-spacecraft can provide power to any of the others. This charging network is constructed using only unmodified off-the-shelf cubesat power subsystem modules.

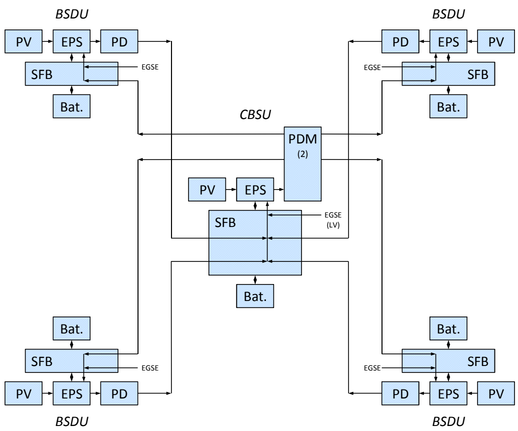

Fig. 8. Power subsystem.charging network

3.3 Photovoltaic Generator

The photovoltaic generators of GOSSAMER-1 consist of operational photovoltaics which provide power for early operations, deployment, and deployment experiment documentation. These are realized using high-efficiency triple-junction PV cells mounted on the external surfaces of the stowed configuration, on all five sub-spacecraft. Each of then can support photovoltaic generator related elements of the Photovoltaics Experiment (PVX), although due to surface area constraints only minor supporting functions can be accommodated on the BSDUs. The main element of the PVX are the thin-film photovoltaic areas on the sail quadrants.

3.3.1 Thin film Photovoltaics: CIGS

The development of thin photovoltaic cells is driven by the need for efficiency, in two ways. First, energy converters for renewable primary energy sources such as sunlight can reach higher yields within given installation constraints or consume less design resources at given power requirements when they work at higher conversion efficiency. Second, their manufacture can provide larger harvesting coverage and installation rate from a given production infrastructure or be less costly and faster to produce for given power requirements when they better utilize the conversion materials.

In photovoltaics, both can be achieved with new semiconductor materials that combine high photoelectric conversion efficiency with good spectral utilization of natural light at short depths of absorption. Such materials, once properly understood in physics and processing, enable the construction of thin film photovoltaic cells on various mechanical substrates.

Mechanical flexibility of the active cell itself merely comes as a potential added bonus to many thin film photovoltaics technologies.

As an example, Fig. 8 shows a CIGS photovoltaics cell on polyimide foil, demonstrating its flexibility and thinness. Fig. 9 shows typical layer structure and thickness of cell layers in CIGS PV technology.


Fig. 9. CIGS cell by Solarion AG, 191 mm x 31 mm. (courtesy Solarion/OC3).

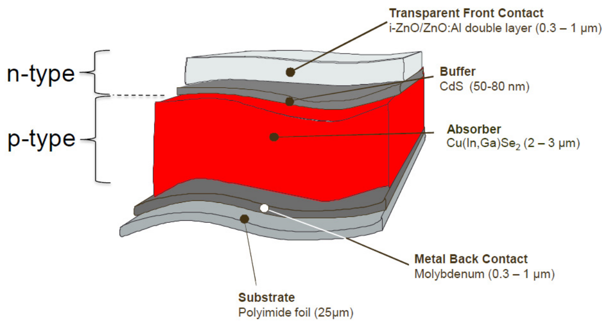

Fig. 9. CIGS cell technology. Layering and thickness of layers are indicated as used in PIPV2 context. Source: C. Kaufmann, HZB Berlin "CIGSspace_KIER".

In space, CIGS cells have proven themselves as highly radiation tolerant. [35] [36] [37] Also, they have achieved a higher efficiency than the well established competing thin-film technology based on amorphous Si as e.g. flown on IKAROS. [31] [32]

3.3.2 Accommodation: Photovoltaic Fields on Sail Segment

The GOSSAMER-1 ground demonstrator is equipped with a thin film flexible photovoltaics (PV) experiment. Each sail segment is equipped with thin film PV fields. Each PV field consists of a number of independent strings/modules of PV cells.

The sail will be stowed in zig-zag folding, see Fig. 10. Therefore, PV elements need to be located in areas without folds, as the PV thin film cells are sensitive to sharp mechanical bending. For electrical connections across folds, suitable approaches were studied and tested.

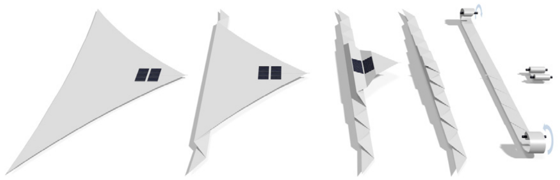

Fig. 10. Sail folding scheme. The folding scheme by which a sail is stowed is shown. PV fields are shown as dark rectangles. They are between folds and facing each other. In the final roll-up of the sail, the central section is mostly rolled onto the spools but remains flat between them. Stowing for launch →, deployment process ←

3.3.3 Geometry of PV Fields on Sail Segment

The GOSSAMER-1 Ground Demonstrator and Qualification Model (QM) contains a single sail segment (or quadrant), boom, and Boom Sail Deployment Unit (BSDU). This quarter-scope QM (¼QM) is sufficient to qualify the complete deployment process involving 4 largely identical modular sections deploying the full square of the sail. A small section towards the inner corner of the sail segment is dedicated to photovoltaics, compare Fig. 11 and Fig. 12. Regarding the general stowing, which consists of folding and rolling, two strips between folds are dedicated to photovoltaics, located between fold lines 3, 4, and 5 (counted from the inner edge and with "0" at the edge itself).

Two types of thin-film PV cells were used, one based on industrial production of CIGS cells used for terrestrial applications (formerly Solarion AG, now OC3 AG) and another based on experimental cells and modules produced at ZSW, Zentrum für Sonnenenergie- und Wasserstoffforschung Baden-Würtemberg.

With respect to the sails symmetry axis, on one half, monolithically manufactured modules based on ZSW technology were used Fig. 11, left half, as seen from hypotenuse facing towards inner sail segment corner, (Fig. 12 far end). On the second half of the sail segment (Fig. 11, right half, as seen from hypotenuse towards inner sail segment corner, Fig. 12 foreground) shingled strings of Solarion modules, so-called Miniature Modules or MiMos were mounted.

In each case modules are arranged in pairs such that within a pair the modules are electrically symmetric relative to the fold line between them (i.e. relative to fold line 4, see Fig. 11).

This arrangement is chosen to prevent damage from accidental surface-to-surface short circuits during deployment.

The symmetry axis of the sail is kept free of PV modules and is reserved as harness corridor.

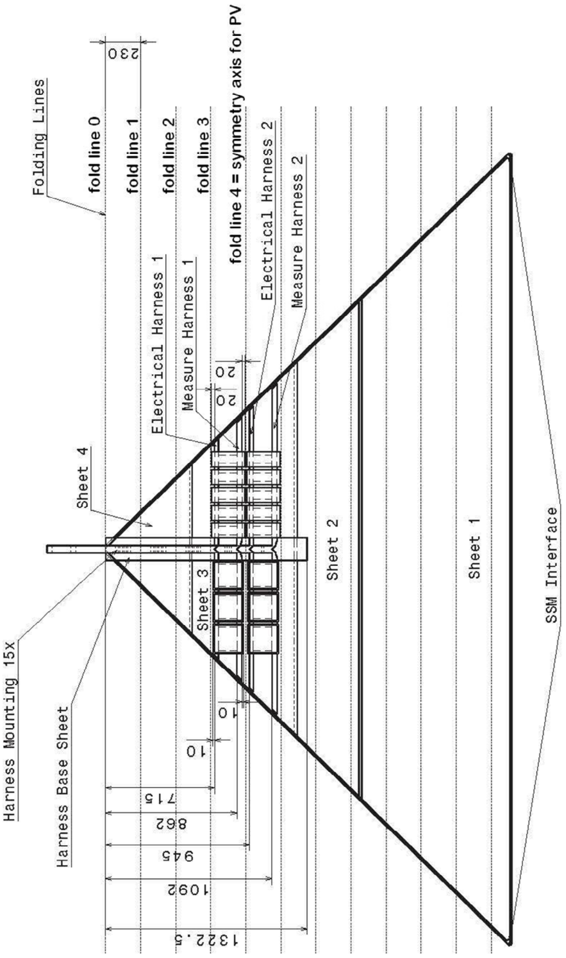

Fig. 11. Design Drawing of a sail segment with PV field. Accommodation of harness and individual PV modules on sail segment is indicated. Also the enumeration of fold lines is explained, to which reference is made from within the text.

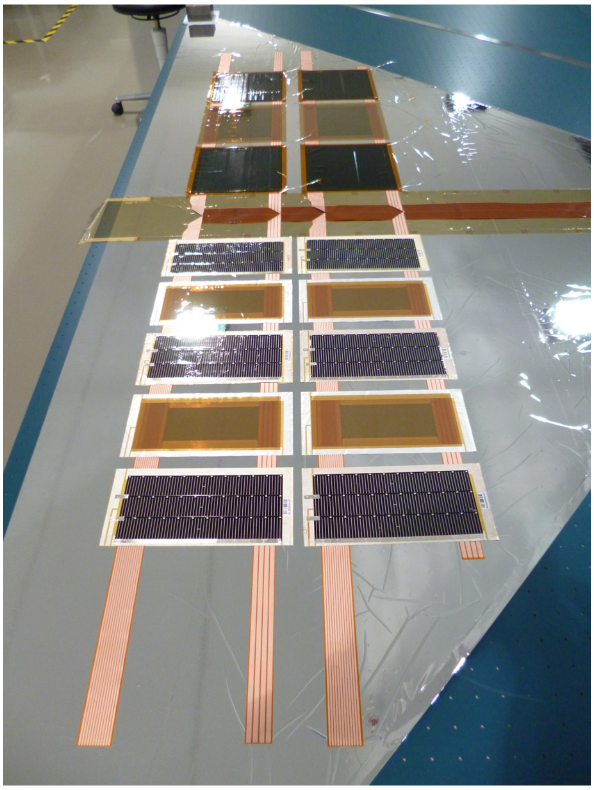
Fig. 12. Photo of the GOS-1 QM sail segement with PV fields and dummies. The harness corridor, visible by the uncoated polyimide foil reinforcement, is at the sail's symmetry axis. The flexPCB based harness segment with 4 broad leads serves as load harness, the other segment with 12 finer leads as measurement harness. In the foreground the Solarion based MiMos are accommodated. They consist of three single PV cells, which are arranged in shingled series connection. In the background the dark and roughly square modules by ZSW are accommodated. Between modules polyimide foil based mass dummies are mounted to simulate a full coverage of the PV field. Spacecraft core and inner corner of the sail connect to the right.

In principle, for full use of the available sail segment surface, all areas between folds are available for the arrangement of PV fields of a sail quadrant. Their size and their location on the sail depend on sail geometry and folding geometry, and can also adapt to specific mission requirements related to e.g. thermo-optical surface properties, shadowing, center of gravity or moment of inertia constraints. In the GOSSAMER-1 design, folds are 23 cm apart, which allows accommodation of PV modules of a width of up to roughly 22 cm.

Solarion MiMos are 219 mm wide at their Cu leads plus an extra 1 mm of foil margin on each side, adding up to 221 mm total width, see Fig. 13. This was driven by the cell geometry of 191 mm cell length and the width of Cu leads at the sides of the cells. Arranging PV cells of this size in shingled geometry into longer strings suggests string accommodation in parallel to fold lines and consequently single cells at 90° relative to fold lines.

ZSW modules were manufactured at a width of 180 mm of CIGS active area and a length of ca. 170 mm, with front contact strip and back contact strip of ca. 5 mm. This module itself is surrounded by 10 mm polyimide foil border for handling and integration.

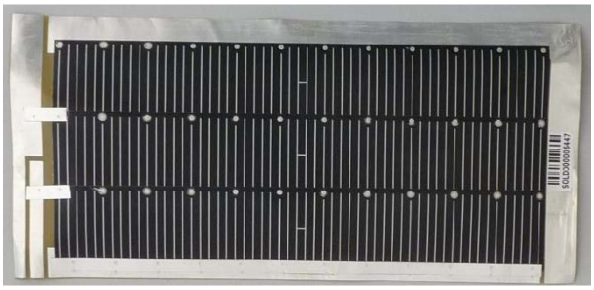

Fig. 13. Photo of Solarion MiMo showing cell integration and all three types of electrical contacts (inter-cell contacting, front contacting (bottom) and back contacting (top)).

3.3.4 CIGS Technology used for the PV Experiment

The experiment uses thin film photovoltaic cells based on CIGS technology on polyimide foil selected for mass considerations, flexibility as well as material compatibility. Independently of GOSSAMER-1 acitivities in DLR's Research & Development (DLR R&D) branch, thin film photovoltaics on polyimide for space applications were being studied within a DLR Space Administration (DLR RM) funded research project called PIPV and PIPV-2, where a follow-up PIPV-3 is presently in preparation. Close informal cooperation between the GOSSAMER-1 project as a potential avantgarde of future technology users and the PIPV consortium provided synergetically optimised cooperation and technology transfer in both directions. From within this consortium came the two main providers for CIGS-on-polyimide during the GOSSAMER-1 project activities, Solarion AG and Zentrum für Sonnenenergie- und Wasserstoffforschung Baden-Würtemberg. Also from the PIPV community, characterisation measurement support is provided by Helmholtz Zentrum Berlin, and SiO_x coating by University of Bayreuth.

Unfortunately, Solarion AG, the key provider of single CIGS PV cells on polyimide for shingled strings, underwent a re-incorporation phase into the newly formed OC3 AG, accompanied by a streamlining of the product portfolio, leading to discontinuation of this design line. The Solarion type CIGS could therefore be implemented only on a significantly reduced scale compared to the original concept for GOSSAMER-1 with a number of MiMos furnished from hardware still in stock to replace full-scale strings. At present, the production line for CIGS cells is however still intact, but it is not clear, if or when production will be started again.

ZSW on the other hand provided modules which are monolithically structured, i.e., the electrical cell series connection is achieved already on low level by suitable combination of laser structuring and layer deposition of the CIGS layers to form the series connection directly "on chip". ZSW CIGS PV cells always come as modules, single PV cells are not available.

However, in the sense of fall-back options, also other types of thin-film PV are likewise useable, e.g. CIGS-on-steel foil or amorphous silicon thin film cells.

Fig. 14 shows an SEM cross section through a CIGS cell as developed and used in the context of the PIPV projects. Clearly visible is the layered structure. The Molybdenum back contact provides the positive contact for the PV cell, while the transparent ZnO layer provides the negative front contact. The SiO_x high-ε layer is applied only after suitable contacting to the ZnO front contact.

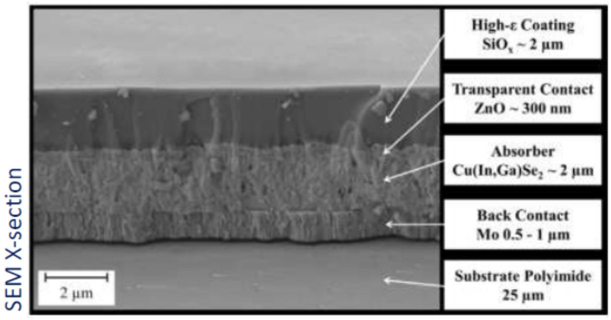

Fig. 14. SEM cross section through CIGS cell as used in PIPV2. Source: C. Kaufmann, HZB Berlin "CIGSspace_KIER".

Fig. 15 shows a schematic of a CIGS PV cell indicating polarity of the layers, which is relevant for electrical contacting between cells.

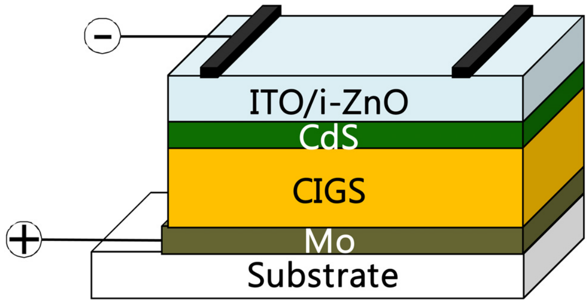

Fig. 15. A schematic of a CIGS thin film PV cell is shown indicating polarity of the layers, which is relevant for understanding the contacting from cell to cell. Source: Lee et al. 2010, DOI: 10.3807/JOSK.2010.14.4.321.

Current density for state-of-the-art mass-produced CIGS PV cells is approx. 30 mA/cm² under terrestrial AM1 conditions, i.e. vertical incidence of sunlight through the Earth's atmosphere. For AM0, i.e., space applications, this value is somewhat larger at about 40mA/cm².

This value together with geometric size of the cells drives the sizing of wires and leads for external contacting.

3.3.4.1 Single cell technology and internal contacting between cells

Solarion AG (now OC3 AG) of Leipzig, Germany, has developed a roll-to-roll process for the production of CIGS photovoltaic cells in a low-temperature process on a lightweight flexible polyimide substrate. These cells were commercially produced, integrated and sold as pre-fabricated modules for building integration. Rigid glass-glass modules and flexible modules in the building-applicable 1 m² thin module size class were available, rated at around 100 W/m² under full terrestrial insolation standard test conditions (STC) of 1 kW/m². Cells were manufactured on 25 µm polyimide film with transfer adhesive at their back for simple and straight forward integration. The size of the cells is 31 · 191 mm².

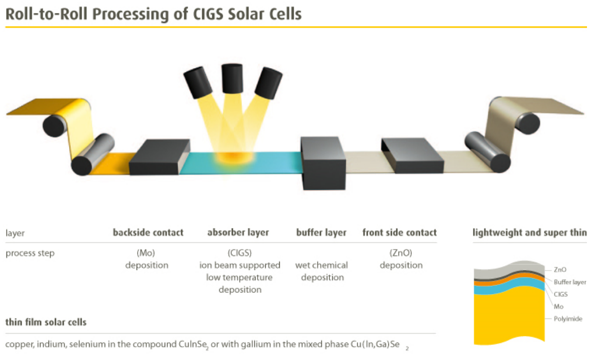

Fig. 16. Roll-to-Roll process as used by Solarion AG.

Electrically, the Solarion PV cells are accessible via the negative front contact which is realised by the comb-like electrical conductors and the horizontal so called bus bar on the top layer of the CIGS cell and the 12 back contact eyes visible at the opposite edge of the cell (see Figs. 9, 13, 17). At these back contact eyes, the positive Molybdenum back contact layer is laid open by localised removal of the CIGS absorber. Through a centred hole at that point, contacting to an underlying lead is possible.

Contacting between cells within a string is done by shingling of cells in such a way, that the back contact side of the second cell is placed on the front contact bus bar side of the first cell. This requires a a corresponding small overlap. Through the holes of the second cell's back contact an electrically conductive connection to the bus bar of the first cell is realised by a drop of electrically conductive adhesive paste at each of these holes. This is repeated for all further cells, whereby electrical strings of in principle arbitrary length, i.e. modules, can be constructed.

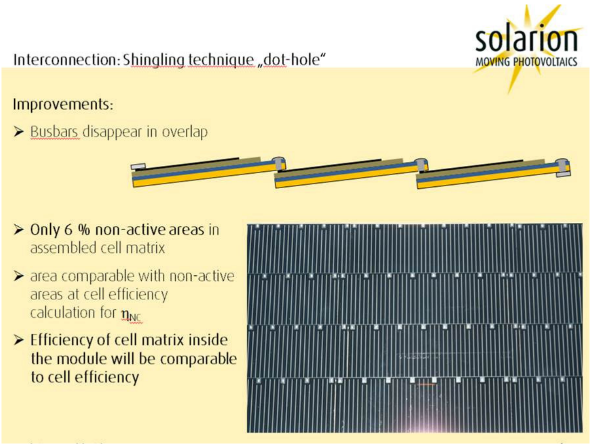

Fig. 17. Illustration of shingeling technique and corresponding cell to cell contacting for forming electrial strings of cells, i.e. PV modules. Image courtesy of Solarion AG. Note that there is an alternating sideways overlap of cells in this terrestrial application PV module which provides added interconnection redundancy and weak cell bypass capability. This connection scheme modifies the module electrical behaviour towards that of a single string. It may also be used in space applications, but is not applied on GOSSAMER-1 because only one cell width fits between two adjacent sail folds, and measurements of single cells and single strings are intended.

The advantage of this approach is that string construction is very flexible and any length of string, i.e. any voltage per module can be achieved by just combining the required number of cells.

Contacting between cells is done using an electrically conductive adhesive or paste, which is a proprietary product developed and used by Solarion AG. However, other commercially available products can also be used. Main driver for development of the proprietary conductive paste was compliance of the paste's physical properties with the automated production in Solarion's industrial production process.

Nevertheless, compatibility of adhesive and the surface properties (i.e. Molybdenum and ZnO) needs to be assured. With respect to space applications, outgassing needs to be compliant with general space requirements.

In the described way, after internal contacting, the front contact (see Fig. 13, lower edge of MiMo) is lead to the side of the MiMo, thereby providing an easily accessible contact for external contacting of the MiMo to the sail's harness (see below). Likewise, the back contact (see Fig. 13, top edge of MiMo) is led to the side of the MiMo.

3.3.4.2 Monolithically manufactured CIGS PV modules (ZSW)

At ZSW, CIGS modules are manufactured on a research and development roll-to-roll pilot production line. Production focusses on monolithically integrated series interconnection in CIGS modules, i.e. to achieve series interconnection on substrate level by combination of laser structuring of CIGS substrate and deposition of layers in suitable sequences. Thereby cell to cell contacting, as required for Solarion cells, is avoided.

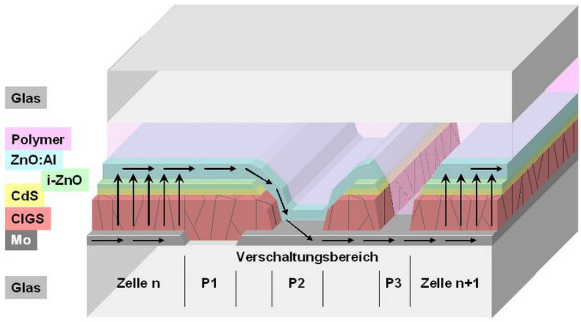

Fig. 18. The principle of monolithically structured CIGS cells is shown. ZSW modules are manufactured according to this. Cell-to-cell contacting is done "on chip".

Modules are manufactured on a specfically selected 25 µm polyimide foil type and can have a width of up to 19 cm. In contrast to the comparatively large Solarion cells, the similarly oriented cells in a monolithically manufactured ZSW module would be quite short, accommodating 32 cells on a geometric string length of only approximately 17 cm.

Fig. 19 shows a ZSW module. It has a size of 180 · 180 mm² and consists of 32 monolithically integrated cells. Front and back contact consist of 4.7mm wide strips at either end of the module (top and bottom in photo), which extend across the full width of the module. Borders between individual cells are visible as thin grey lines. Cells are only a few millimetres long and cover the full module width of 180 mm.

Due to monolithical integration of the cells no cell-to-cell contacting is required, and also, no additional substrate layer is needed for this purpose. This is an advantage of the monolithical approach. Monolithically manufactured ZSW modules can be directly externally contacted.

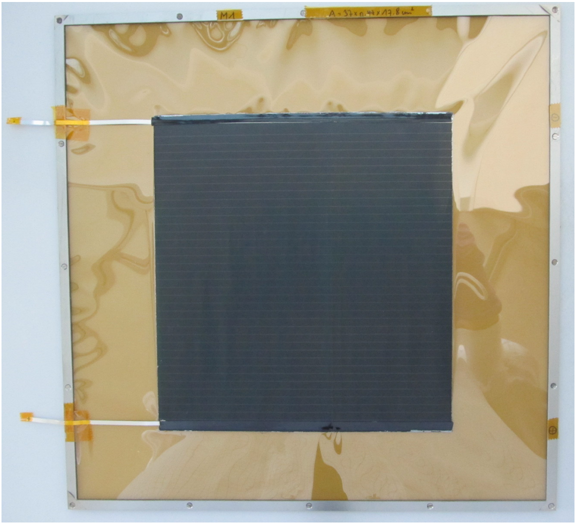

Fig. 19. A ZSW module is shown, which is of 180 · 180 mm², including 4.7 mm on each side (see top and bottom contact strip) for front contact and back contact. Horizontal lines indicate the borders between monolithically integrated, series-connected individual PV cells. The module consists of 32 cells. Front contact and back contact are already contacted using conductive tape leading the contacts to the left side of the module.

3.4 On-Sail Harness

Layout of sail harness is mainly driven by the following aspects:

- electrical layout, i.e. single module connections or series/parallel connections
- number of modules per PV field
- number of measurement connections required
    - sub-module level or cell-level monitoring,
    - temperature measurements
- mechanical compatibility with sail folding scheme
- dimensioning of cross section based on electric current and temperature

3.4.1 FlexPCB based harness

For the on-sail harness of the GOSSAMER-1 QM sail quadrant (Fig. 1-5), a FlexPCB-based design was chosen, where all conductors are realised as Cu-leads in FlexPCB-like manner. Fig. 20 shows an example of such harness material.

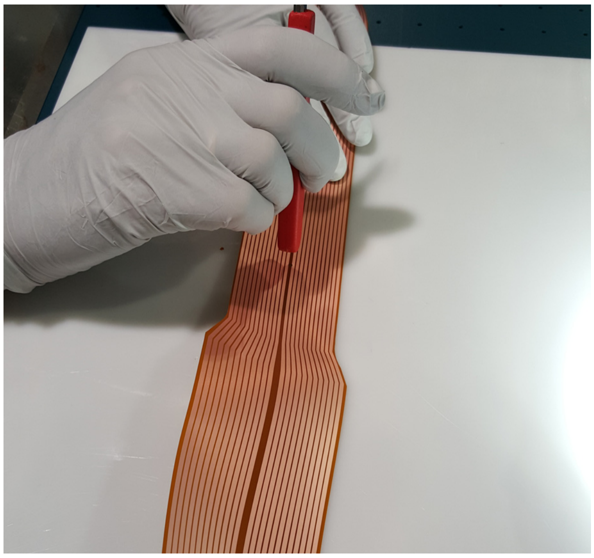

Fig. 20. FlexPCB-like harness. As an example a measurement harness is shown, based on Krempel KCL 2-17/50 HAT.

On each half of a sail segment (i.e. one half to the left of the sails symmetry axis and one half to the right of the sails symmetry axis) each PV field (PV strings between folds) would be connected by one load harness and one measurement harness.

Harnesses originating from PV fields from each sail half would have to be accommodated side by side at the sail's symmetry axis, in the so called harness corridor. This requires the harness to be folded in a way that a 90° change of direction for the harness is achieved, see Fig. 12.

As there are several PV fields, one between each fold, the corresponding harnesses is accommodated in the harness corridor at the sail's symmetry axis stacked one on top of another.

3.4.2 Electrical dimensioning of harness

The electrical harness is subdivided into load harness and measurement harness. The load harness carries the full electric load produced by the PV modules and consumed by the electric loads at the spacecraft.

Electric current in the measurement harness is generally of the order of µA to a few mA, which for standard dimensioning of PCB leads is uncritical. Measurement harness leads are laid out to have 17 µm thickness (FlexPCB Cu layer thickness) and 2 mm width providing a 0.034 mm² cross section corresponding to AWG 32.

For dimensioning of the load harness the maximum current produced by the PV cells needs to be considered as well as the electrical arrangement of modules, i.e. one harness lead pair per module or parallel or series connection of several modules.

For GOSSAMER-1 it was decided to have one harness lead pair per module, which has two key advantages:

- With GOSSAMER-1 being a demonstrator, individual harness lead pairs per module provide the possibility to monitor each module individually, which provides the maximum learning about PV module performance in space.
- By providing one harness lead pair per module it is possible to accommodate the back current diodes within the electronics compartment of the space craft instead of having to accommodate them on the sail, which would become necessary if series-parallel connections on the sail were selected.

Regarding cumulated cross section within the main harness, this approach does not introduce additional Cu lead cross section, as the total cross section required for conducting a specific current remains roughly the same.

This holds, as long as only parallel connection of modules is considered, i.e. the mode of connection does not change resulting voltage, but adds up currents.

Series connection of modules could be considered as a means to reduce current. However, this is limited by increasing risk of electrical arcing at higher voltages. On this background, e.g. solar panel voltages at the ISS are limited to 150 V.

For GOSSAMER-1 with the selected Clyde Space CubeSat Power System (CS-XUEPS2-41-42) the maximum input voltage is limited to 25 V. This is well below arcing critical voltages.

However, for larger designs as planned for GOSOLAR, arcing and related maximum acceptable voltage needs to be studied, especially as this will be a means for limiting harness cross section.

Having decided on individual harness lead pairs per module, harness cross section dimensioning for load harness lead pairs is then only driven by maximum current per module.

Current density for CIGS PV cells is approx. 40 mA/cm² at AM0 for space applications. Based on the different cell geometries, maximum electric current in the load harness differs strongly between Solarion MiMos and ZSW modules.

For Solarion MiMos this results in a considerable maximum current of approximately

$$28\ \text{mm} \cdot 191\ \text{mm} \cdot 40\ \text{mA/cm}^2 = 53.48\ \text{cm}^2 \cdot 40\ \text{mA/cm}^2 = \mathbf{2.14\ A}$$

In this calculation, the cell shingling overlap was considered. Since the minimum current cell approximately fixes the string current, the illuminated area of the last cell not overlapped by another does not significantly affect the result.

For ZSW modules this value is much smaller due to much smaller cells in ZSW modules:

Full module active area:
$18\ \text{cm} \cdot 16\ \text{cm} = 288\ \text{cm}^2$
32 cells per module:
$288\ \text{cm}^2 / 32 = 9\ \text{cm}^2$ per cell
Maximum current:
$9\ \text{cm}^2 \cdot 40\text{mA/cm}^2 =$ **360 mA**

Dimensioning of the harness was done based on derating recommendations as given in MIL-STD-975 and GSFC-PPL-17, -19 or -21.

The harness trunk in the harness corridor is considered as a wire bundle. Maximum allowable temperature was set to 150°C, resulting in 80% of recommended values. 150°C as design temperature leaves leeway to the maximum allowable temperature on the sail, which is defined by maximum allowable temperatures of polyimide membrane and transfer adhesive. For both materials temperatures well beyond 200°C are allowable. This margin is required, as derating values according to the cited MIL standards and GSFC standards assume 70°C environment temperature. This will be higher on PV sails.

For illustration, the same considerations are also presented for 105°C maximum allowable temperature, which would lead to even larger Cu cross-section.

The following table lists the results obtained for 105°C maximum allowable temperature:

Table 2. Harness sizing for 105°C max. temperature

source	max. current (AM0)	AWG: mm² *	assumed flexPCB lead width	resulting min. lead thickness
Solarion MiMo	2140 mA	**22: 0.324** 18: 0.823	5 mm	**65 µm** 165 µm
ZSW Module	360 mA	**30: 0.0506** 28: 0.0804	5 mm	**10.1 µm** 16.1 µm

* based on MIL-STD-975 (**105°C**), **single**/bundle

The following table lists the results obtained for 150°C maximum allowable temperature:

Table 3. Harness sizing for 150°C max. temperature

source	max. current (AM0)	AWG: mm² *	assumed flexPCB lead width	resulting min. lead thickness
Solarion MiMo	2140 mA	**24: 0.205** 20: 0.519	5 mm	**65 µm** 165 µm
ZSW Module	360 mA	**30: 0,0506** 30: 0,0506	5 mm	**10.1 µm** 16.1 µm

* based on MIL-STD-975 (**150°C**), **single**/bundle

For the GOSSAMER-1 ground demonstrator a compromise regarding lead thickness was made by choosing readily available KCL 2-17/50 HAT, i.e. 50µm polyimide and 17mm Cu layer thickness as base material. This compromise was necessary as FlexPCB manufacturing was experimental and selecting standard thickness reduced manufacturing risk. At the same time this compromise reduced cost significantly, which was a general key requirement regarding realisation of the ground demonstrator before the end of 2015.

Regarding use of the ground demonstrator this compromise is not critical, as characterisation measurements can be performed at different air mass factors, i.e. different light intensities. These can be scaled to the maximum allowable current as defined by the Cu layer thickness chosen.

In view of scalability of dimensioning for future realistic missions, the following degrees of freedom exist:

- Increase of thickness in next harness prototype, based on positive experience with present prototype.
- Increase the width of leads by increasing harness trunk width. For GOSSAMER-1 this was limited by the geometrical accommodation envelope, which was originally defined by the shared launch option with the QB50 project and its launcher negotiations.
- Doubling of lead width by splitting an individual load harness into two stacked layers in main trunk.
- Increase the string voltage to reduce current at a given power level.

The limitations, which lead to the selected compromise, will not apply for GOSOLAR or any other realistic future mission. Rather, any harness design drivers will have to be considered as design drivers for the mission design as such, as harness performance will count among the key performance parameters of a large deployable thin film solar array.

3.5 Sizing of the PV string: Number of Cells in String

Sizing of the strings is in first place driven by the requirement on a realistic power supply scenario for the PV Experiment. Therefore the voltage of the strings has to be such that it is compatible to the S/C power subsystem electronics. As temperature plays a key role in PV performance, it has to be kept within realistic limits, thereby driving the thermal layout. For electric sizing, a temperature range of approximately -100°C to +100°C was considered.

3.5.1 Off-the-Shelf Interface Requirements

COTS-available EPS hardware from the cubesat sector uses two standard solar power converter topologies which both support combined Maximum Power Point Tracking Battery Charge Regulator (MPPT-BCR) nested control loops.

The low-power, typical 1U cubesat converter is a SEPIC or step-up (boost) converter; the latter requires that the solar array voltage is always below battery voltage. The high-power, typical 3U- and larger cubesat converter is a step-down (buck) converter which requires that the solar array voltage is never below the battery voltage.

Cubesat EPS commonly use 2s*m*p Li-ion or Li-polymer batteries with a cell voltage range of 2.5…3.0 V end-of-discharge voltage (EODV) and 4…4.2 V end-of-charge voltage (EOCV). Thus, the small power converters have to operate well below 5…6 V output voltage and are designed for two 2s*m*p connected triple-junction cells. 40 · 80 mm² cells can cover a very large fraction of a 1U cubesat panel, i.e. *m* typically = 1. Thus, 'small' converters are usually designed for 3…4.5 W input power. The 'large' power converters have to operate well above 8…8.5 V output voltage and, though operating at the same current, are designed for longer strings of 40 · 80 mm² triple-junction cells and 8…12 W input power, i.e. 6..8s*m*p, *m* = 1..3.

Higher power capable PV cells or arrays may be used but the MPPT-BCR will then enter a current-limited regime under full (near-vertical) illumination and only track the MPP properly once illumination is reduced. Depending on the detailed MPPT-BCR design the current may have to be limited externally to the EPS.

The 'small' converter type will also have a minimum operation voltage required to start up, and the large converter a maximum operating voltage based on component ratings. (Within bounds, the latter may be extended by replacing a few devices by higher-rated components and adapting the values of others accordingly, without changing long-lead items such as PCB routing design, but this was out of scope of the GOSSAMER-1 project).

For a 12 W class converter with 25 V maximum input voltage, strings of 32 Solarion CIGS cells result for -100°C minimum temperature and a V_{oc} temperature coefficient of -0.35%/K (or -2 mV/K, typical of any pn junction). Such a string leaves the MPPT tracking regime towards approximately constant voltage operation at about +80°C when the string voltage at MPP drops below the minimum input voltage of e.g. 10 V due to the same temperature coefficient. Due to the large cell area of the Solarion CIGS cells, the full current the cells can provide can not be used by presently available converters, and at 0.75 A a current-limited operation is entered, at approximately <70° solar array normal to Sun angle (SAN2Sun). On the other hand this means that shallow illumination is well MPPT'd which may be useful for a tumbling spacecraft.

The situation for a small converter is similar, resulting in strings of 10..13 Solarion CIGS cells and a MPP departure point near 50…110°C, respectively.

The ZSW modules' much lower string current on the other hand fits well with off-the-shelf CubeSat hardware, being a little less than half the typical input current limit. Two of these strings can be connected to one MPPT-BCR channel in CubeSat manner on 180° opposed faces of the spacecraft, or in this case on the top and bottom sail surfaces, without leaving the MPPT regulation regime when illuminated by Sun and Earth albedo combined.

3.6 Measurement of individual cells

Measurement of individual cells is driven by the objective to monitor and characterise performance of the PV Experiment's components, particularly the CIGS cells and the harness.

The selection of the cells which are to be measured individually is driven by the fact, that the number of available analogue inputs is limited. Therefore, not all, but only some of the cells can be monitored.

Solarion MiMos are laid out such that each of the three cells can be measured individually. Connections to the measurement harness are foreseen. As the number of leads in the measurement harness (12) does not allow for 4 wire measurement at all cells, a 2-wire measurement connection is foreseen with all cells operating on the same current which they generate. Effectively, this creates a 4-wire equivalent setup, although the current can not be set arbitrarily but is defined by orientation of the spacecraft. Therefore, accurate measurement of the Sun vector is required, using co-operating fine and coarse Sun sensors.

ZSW modules being monolithically manufactured do not provide access to individual cells within the monolithic structure. Hence, they are only measured at module level, the same way as Solarion cells.

In case of future large single-cell based strings, monitored single cells from within a string will be selected based on a pseudo-statistical pattern to catch effects along the length of the string at different points within different strings.

3.7 Coating of photovoltaic cells with SiO_x

There are different aspects which suggest consideration of coatings for thin film photovoltaics:

- CIGS sensitivity to humidity
- CIGS sensitivity to mechanical abrasion
- sub-optimal thermal emissivity of uncoated CIGS cells
- ATOX sensitivity of unprotected polyimide used in the context of photovoltaics, e.g. Solarion MiMo FlexPCB as well as ZSW FlexPCB

Within the PIPV project, a coating technique was developed at University of Bayreuth, which is suitable to apply an approx. 2 µm thin SiO_x layer onto CIGS cells as well as CIGS modules as well as on arbitrary foil objects. The method allows definition of layer thickness and thereby allows trimming thermal emissivity. The stated 2 µm thickness was determined within the project's context to provide values for thermal emissivity ε of approximately 0.8.

At the same time this layer could be shown to be mechanically sturdy and with high adhesion to CIGS cells as well as polyimide. This was verified by standard cross hatch ASTM D 3359 test procedures. The SiO_x layer also has good water vapour barrier properties.

Solarion MiMos as well as ZSW modules were coated with 2 µm SiO_x at the University of Bayreuth by the described technique.

Dedicated characterisation measurements using DLR Bremen's laboratory equipment are planned as part of the GOSSAMER-1 qualification campaign.

In the following chapters basic background information regarding the individual effects are summarised.

3.7.1 Humidity

CIGS PV cells are sensitive to humidity. Therefore all Solarion and ZSW manufacturing processes take this into account. Exposure of PV cells to ambient air is limited. However, the larger part of this time the cell is covered within a roll of material. Only some hours it is indeed exposed directly to free air.

Apart from this the PV cells are stored under protective N_2 atmosphere or in evacuated bags, as normally used for sensitive electronic equipment.

It is anticipated that sensitivity to bending depends on exposure to ambient humidity.

Therefore at DLR the same protective measures have to be taken and the manufacturing process needs to take into account the limitation of exposure to ambient, i.e. non-dried, air.

A considerable number of dedicated studies have been performed and development is still ongoing in the CIGS community to produce mechanically sturdy coatings which at the same time provide high water vapour barrier properties. These barrier properties are all aiming at survival of CIGS cells under moist terrestrial conditions and over life times targeted in the order of decades. Therefore such coatings would provide in any case sufficient protection for CIGS, which would be exposed only to climate controlled interior for limited time and worst case some days on a launcher under ambient conditions, if at all ambient.

3.7.2 Mechanical abrasion and bending sensitivity

CIGS cells are only a few microns in thickness. They are hard and crystalline, therefore they tend to behave brittle. A sturdy mechanical coating, which at the same time is transparent in the sensitive wavelength range of the CIGS cell, would be suitable to protect the cell against mechanical damage.

3.7.3 High epsilon coating

Thermal emissivity of bare CIGS cells is low. Therefore CIGS cells tend to get hot, when being exposed to sunlight. Electrically, performance of CIGS cells depends critically on temperature. High temperatures reduce efficiency of PV cells. Therefore a design goal regarding temperature range was defined in the order of -100°C to +100°C.

Within the PIPV project team, studies were made how to apply commercially available as well as specifically designed coatings to CIGS cells in order to produce specific thermal emissivities. Such high emissivity coatings are by now available, see above. However, specific thermal studies including corresponding testing are yet to be performed.

3.7.4 Peeling test regarding adhesion of standard Kapton tape to SiO_x coating

Regarding adhesion of standard Kapton tape to an SiO_x coated surface, specific peeling tests along ASTM D3330 guidelines were performed to validate the chosen design. These included adhesion between the Kapton tape type 3M 1205 widely used in space applications and coated polyimide film as well as between the this type of Kapton tape and a SiO_x surface produced by the coating technique described. Similar tests for other transfer adhesives and regarding coating variations are yet to be performed.

3.7.5 Bending sensitivity of PV cells and contacting

PV cells, but also the contacting between PV cells is sensitive to mechanical loads introduced by bending. The bending radius is a key parameter here, but also the direction of bending relative to the PV cell's geometry, i.e., the bending axis being aligned with the long side or the short side of the cell, and direction towards its front side or its back side.

At Solarion's production lines the PV cells are bent across drums of a standardized diameter. Bending occurs in both directions, i.e. across the front side as well as the back side. The bending axis is parallel to the collector fingers of the front contact, i.e parallel to the short side of the cell.

The diameter of a GOSSAMER-1 Sail Spool Mechanism roll core is 30 mm, which considering that the cells in GOSSAMER-1 are in the last area to be rolled up, is roughly a factor of 2 smaller than the smallest diameter experienced in the Solarion manufacturing line. Therefore bending tests are explicitly required.

In the preliminary bending tests performed at DLR the cells were pulled across a roll. This introduced bending, but also a small longitudinal stress into the PV cell, which is not necessarily consistent with the real application on the sail. Although this stress was carefully kept at a minimum, the results of this preliminary test have to be considered with care.

Sample strings including contacting within the string as well as contacting of the ends of the string are planned to be subjected to further bending tests. Only if problems with the tested string occur, these tests shall be performed with individual PV cells as such. Bending tests will be performed with existing bending test facilities. Before and after bending tests the strings shall be characterised (I-V characteristic curve and electroluminescence) using existing characterisation facilities.

3.7.5.1 Further Testing - Bending cycle test

In manufacturing, stowing and deployment of the GOSSAMER-1 sail, a minimum of 2 bending cycles of flight hardware would be required:

- stowing for test deployment (straight → bent)
- test deployment on ground (bent → straight),
- stowing for launch (straight → bent)
- deployment in space (bent → straight).

For qualification, the bending tests are performed with a significant cycle count margin and on three test samples consisting of fully assembled PV strings and their immediate interfaces to the sail. In GOSSAMER-1 the PV cells of one PV tile can be bent across their back or their front side. Therefore the bending test needs to include two samples, one for each bending turn direction. In GOSSAMER-1 the cells are only bent along their short side, i.e. a matrix test is not required.

However, bending sensitivity depending on aging, mainly due to exposure to humidity of cells may require a specific dedicated test.

3.7.5.2 Further Testing – Long-term storage test

As GOSSAMER-1 will most likely remain stowed for a considerable duration of the order of several months, it needs to be verified by long term storage tests that PV cells do not degrade by this long-term bent storage. A long term bent storage test would be performed with a duration goal of several months, approximating a likely piggy-back launch scenario. Storage in a protective (or if necessary, inert) atmosphere at ambient pressure and temperature simulates a waiting period at DLR, followed by a period simulating exposure to air during the launch vehicle integration campaign and possible launch delays which are also of the order of months, each.

Other factors may be included in these system-level tests but can also be performed at unit or component level, e.g. thermal cycling variation of the number of bending cycles, variation of the duration of bent (i.e., stowed) storage, peeling test regarding creep of the transfer adhesive, migration of the adhesive or parts thereof from beneath the PV cell to exposed areas, and possible resulting layer-to-layer sticking accidents on the sail spool.

3.8 Materials and Processes

3.8.1 Solarion MiMos

Solarion MiMos consist of different components, which are the CIGS material as such, the Solarion specific contacting paste, conductive ink used for the front contact collector grid, the polyimide substrate, transfer adhesive below the substrate as well as in the final form the SiOx coating on the front of the MiMo.

Considering these MiMos as a composite, these were subjected to an outgassing test according to ECSS-Q-ST-70-02C standard.

Results were within the range defined by the said standard:

RML < 1.00% and CVCM < 0.10%

(RML: Recovered Mass Loss, CVCM: Collected Volatile Condensable Material)

Results from the test (DLR-UHV-016-2015) are:

Table 3. Outgassing Test Results

TIIN (Test Item Identi-fication No)	TML [%] (Total Mass Loss)	RML [%] (Recovered Mass Loss)	CVCM [%] (Collected Volatile Condensable Material)
523/15	**0.98** (0.01)	**0.63** (0.01)	**0.03** (0.00)
524/15	**1.02** (0.07)	**0.67** (0.05)	**0.06** (0.02)

* average of three test runs, in brackets (.) the resulting standard deviation

4. Conclusions

The integration campaign and first operations of the GOSSAMER-1 Ground Demonstrator and Qualification Model (QM) provided extremely valuable practical experience for the design of future lightweight spacecraft with deployable photovoltaics or other large lightweight deployables. After the termination of the GOSSAMER-1 project at the end of 2015, the team and its experience gained on GOSSAMER-1 is seamlessly continued into our new project, GOSOLAR. The focus is now entirely on gossamer deployment systems for huge thin-film photovoltaic arrays.

Based on the previous achievements in the field of deployment technology and qualification strategies, new technology for the integration of thin-film photovoltaics is being developed and will be qualified for a first in-orbit technology demonstration expected to achieve flight readiness within about five years. The two major objectives of the project are the further development of deployment technology with adaptations for a 25 m² gossamer solar power generator and the development of a flexible photovoltaic membrane. The technology demonstration is slated to employ the S²TEP bus system which is developed on-site in parallel. [38]

There are significant challenges ahead: The level of power required in the solar array application is about two orders of magnitude higher than for a sailcraft of the same size. The currents required to carry power off the thin-film structure at commonly used bus voltages result in a substantial harness cross-section. At the same time, there is a desire for higher voltages, e.g. to power electrical propulsion directly. The change from GOSSAMER to GOSOLAR also means a change of perspective from an independent small and lightweight experimental spacecraft (or a constellation of five such, counting the BSDUs) to a sub-subsystem function on a potentially huge and heavy mainstream standardized spacecraft.

In consequence the first system GOSOLAR will be a low voltage system employing off-the-shelf small spacecraft power system technology wherever possible, and an experiment payload aboard a small experimental spacecraft which it can power whenever possible.

Integration of this mission on a demanding schedule will benefit from the Concurrent AIV methods practised on MASCOT. [39][40] The development of full-scale high power systems will be studied in parallel and its implementation is left to future projects. Their development will benefit from Model-Based System Engineering (MBSE) methods developed in the context of MASCOT, its follow-on studies and for DLR contributions to the ROBEX project. [41][42][43]

Using an established test strategy, a characterization of the deployment performance and deployment forces will be made based on a test-as-you-fly approach. It includes vibration testing, fast decompression, partial deployment under thermal-vacuum and full-scale ambient deployment on a test rig previously developed for GOSSAMER-1. The data gained can be used for further development and as input for mechanism and structure sizing.

Examples for the application of those development and testing strategies are the previous DLR GOSSAMER-1 project, the ESA drag sail projects 'Deployable Membrane' and 'Architectural Design and Testing of a De-Orbiting Subsystem' (ADEO) as well as the tether deployment of the HP³ experiment on the NASA/JPL Mars mission INSIGHT.

Acknowledgements

This work was funded by DLR German Aerospace's Research and Development program for technology of space systems as "GOSSAMER-1 Deployment Technology Demonstrator Project". The launch opportunity was funded by EC-Project "QB50", Project Identifier 284427, FP7-SPACE-2011-1, "QB50-An international network of 50 CubeSats for multi-point, in-situ measurements in the lower thermosphere and re-entry research". The authors appreciated the fruitful and constructive cooperation with all QB50 and EC representatives.

The authors wish to express their gratitude for excellent technical discussions, review support and advice by ESA/ESTEC-TEC-M and D/TEC-MTT. Regarding solar sail specific mission design the authors are indebted to ESA ESTEC TEC-M for organizational support, and to Bernd Dachwald (University of Applied Sciences Aachen), Malcolm Macdonald (University of Strathclyde) and Collin McInnes (University of Glasgow) for leading three independent solar sail candidate mission studies. Furthermore, the authors want to thank their project partners at University of Würzburg, Aerospace Information Technology as well as at RWTH Aachen, Institute of High Frequency Engineering for fruitful cooperation and discussion.

And finally our thoughts are with late Ruedeger Reinhard, together with Jean Muylaert from VKI Brussels one of the godfathers to QB50 and GOSSAMER-1 within QB50.

As ESA Consultant, Ruedeger's everlasting initiative and diplomacy brought people together, brought projects into existence and without him this project would never have reached the stage of maturity, which it has reached by now, no matter, which obstacles still pertain. He inspired people and created visions. The world needs more people of this kind. Instead, we grieve for him, having one less of his kind among us.

References

[1] J. Kepler, De Cometis Libelli Tres, 1619.
[2] J.C. Maxwell, A Treatise on Electricity and Magnetism (1st ed.), 2, 391, Oxford, 1873. (cf. [5])
[3] A. Bartoli, Sopra I movementi prodotti della luce et dal calorie, Florence, Le Monnier, 1876; also Nuovo Cimento, 15, 193, 1884. (cf. [5])
[4] P. Lebedev, Untersuchungen über die Druckkräfte des Lichtes, Annalen der Physik, 1901
[5] E.F. Nichols, G.F. Hull, The Pressure due to Radiation, Phys. Rev. (Series I) 17, 91-104, 1903
[6] John Perlin, A short summary of the evolution of photovoltaics, © 2015, http://californiasolarcenter.org/history-pv/, (accessed 06SEP2016).
[7] Don P. Mitchell, Sputnik-3, © 2007, http://mentallandscape.com/S_Sputnik3.htm, (accessed 06SEP2016).
[8] J.T. Grundmann, J. Biele, R. Findlay, S. Fredon, T.-M. Ho, C. Krause, S. Ulamec, C. Ziach, One Shot to an Asteroid – MASCOT and the Design of an Exclusively Primary Battery Powered Small Spacecraft in Hardware Design Examples and Operational Considerations, № 3051, European Space Power Conference 2014.
[9] C. Ziach, V. Baturkin, T.-M. Ho, C. Grimm, J.T. Grundmann, C. Lange, N. Termtanasombat, R. Findlay, J. Reill, M. Lange, O. Mierheim, J. Biele, C. Krause, S. Ulamec, B. Borgs, M. Grott, R. Jaumann, M. Deleuze, J.-P. Bibring, H.-U. Auster, and the MASCOT Project Team, MASCOT, the Small Mobile Asteroid Landing Package on its Piggyback Journey to 1999 JU3: Pre-Launch and Post-Launch Activities, IAC-15-A3.4.6
[10] Tra-Mi Ho, Volodymyr Baturkin, Ross Findlay, Christian Grimm, Jan Thimo Grundmann, Catherin Hobbie, Eugen Ksenik, Caroline Lange, Kaname Sasaki, Markus Schlotterer, Maria Talapina, Nawarat Termtanasombat, Elisabet Wejmo, Lars Witte, Michael Wrasmann, Guido Wübbels, Johannes Rößler, Christian Ziach, Jens Biele, Christian Krause, Stephan Ulamec, Michael Lange, Olaf Mierheim, Roy Lichtenheldt, Maximilian Meier,

Josef Reill, Hans-Jürgen Sedlmayr, Pierre Bousquet, Anthony Bellion, Olivier Bompis, Céline Cenac-Morthe, Muriel Deleuze, Stephane Fredon, Eric Jurado, Elisabet Canalias, Ralf Jaumann, Jean-Pierre Bibring, Karl Heinz Glassmeier, David Hercik, Matthias Grott, Luca Celotti, Federico Cordero, Jeffrey Hendrikse, Tatsuaki Okada; MASCOT - The Mobile Asteroid Surface Scout onboard the Hayabusa2 Mission; Space Science Reviews 2016

[11] J. Biele, S. Ulamec, M. Maibaum, R. Roll, L. Witte, E. Jurado, P. Muñoz, W. Arnold, H.-U. Auster, C. Casas, C. Faber, C. Fantinati, F. Finke, H.-H. Fischer, K. Geurts, C. Güttler, P. Heinisch, A. Herique, S. Hviid, G. Kargl, M. Knapmeyer, J. Knollenberg, W. Kofman, N. Kömle, E. Kührt, V. Lommatsch, S. Mottola, R. Pardo de Santayana, E. Remetean, F. Scholten, K.J. Seidensticker, H. Sierks, T. Spohn, The landing(s) of Philae and inferences about comet surface mechanical properties, Science, Vol.349, issue 6247, aaa9816-1 (2015).

[12] E. Hand, Comet lander's scientific harvest may be its last – Philae has fallen silent after fragmentary messages, Science, Vol.349, issue 6247, 459-460 (2015); also cf. M. Braun, K. Geurts, S. Ulamec, New command for Philae, http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10081/151_read-16365/#/gallery/21643

[13] Wilson, A. (Ed.), Huygens: Science, Payload and Mission, ESA SP-1177.

[14] Andrew Ging, Regaining 20 Watts for the Cassini Power System, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Nashville, AIAA 2010-6916.

[15] W. Seboldt, M. Leipold, M. Rezazad, L. Herbeck, W. Unkenbold, D. Kassing, M. Eiden. Groundbased demonstration of solar sail technology. Rio de Janeiro, Brazil, 2000. 51st International Astronautical Congress, IAF-00-S.6.11.

[16] M. Leipold, C.E. Garner, R. Freeland et al., ODISSEE - A Proposal for Demonstration of a Solar Sail in Earth Orbit, 3rd IAA International Conference on Low-Cost Planetary Missions, Laurel, Maryland, April 27 - May 01, 1998.

[17] M. Leipold, M. Eiden, C.E. Garner et al., Solar Sail Technology Development and Demonstration, 4th IAA International Conference on Low-Cost Planetary Missions, Laurel, Maryland, May 2-5, 2000.

[18] E.K. Jessberger, W. Seboldt, K.-H. Glassmeier, G. Neukum, M. Pätzold, G. Arnold, H.-U. Auster, D. deNiem, F. Guckenbiehl, B. Häusler, G. Hahn, N. Hanowski, A. Harris, H. Hirsch, E. Kührt, M. Leipold, E. Lorenz, H. Michaelis, D. Möhlmann, S. Mottola, D. Neuhaus, H. Palme, H. Rauer, M. Rezazad, L. Richter, D. Stöffler, R. Willnecker, J. Brückner, G. Klingelhöfer, T. Spohn, ENEAS – exploration of near-Earth asteroids with a sailcraft, Technical report, August 2000, Proposal for a Small Satellite Mission within the Space Sciences Program of DLR.

[19] B. Dachwald, W. Seboldt, Multiple near-Earth asteroid rendezvous and sample return using first generation solar sailcraft, Acta Astronautica, 57(11):864–875, 2005.

[20] M. Macdonald, G.W. Huges, C.R. McInnes, et al., GEOSAIL: An Elegant Solar Sail Demonstration Mission, Journal of Spacecraft and Rockets, Vol. 44, No 4, pp 784 – 796, 2007.

[21] D. Agnolon, Study Overview of a Solar Sail Demonstrator: GEOSAIL, ESA, SCI-PA/2007/018/Geosail, date of issue: 09/01/2008.

[22] M. Leipold, M. Macdonald, C.R. McInnes, et al., GEOSAIL System Design for Demonstration of Solar Sailing in Earth Orbit, Proceedings of the Second International Symposium on Solar Sailing (ISSS 2010). The New York City College of technology of the City University of New York, July 2010.

[23] U. Geppert, B. Biering, F. Lura, J. Block, R. Reinhard, The 3-Step DLR-ESA GOSSAMER Road to Solar Sailing, ISSS, 2010.

[24] U. Geppert, B. Biering, F. Lura, J. Block, M. Straubel, R. Reinhard, The 3-Step DLR–ESA GOSSAMER road to solar sailing, Advances in Space Research 48 (2011) 1695-1701. .

[25] C.R. McInnes, V. Bothmer, B. Dachwald, U.R.M.E. Geppert, J. Heiligers, A. Hilgers, L. Johnson, M. Macdonald, R. Reinhard, W. Seboldt, P. Spietz, Gossamer Roadmap Technology Reference Study for a Sub-L1 Space Weather Mission, in: M. Macdonald (ed.), Advances in Solar Sailing, 2014 (3rd International Symposium on Solar Sailing)

[26] M. Macdonald, C. McGrath, T. Appourchaux, B. Dachwald, W. Finsterle, L. Gizon, P.C. Liewer, C.R. McInnes,G. Mengali, W. Seboldt, T. Sekii, S.K. Solanki, M. Velli, R.F. Wimmer-Schweingruber, P. Spietz, R. Reinhard, Gossamer Roadmap Technology Reference Study for a Solar Polar Mission, in: M. Macdonald (ed.), Advances in Solar Sailing, 2014 (3rd International Symposium on Solar Sailing)

[27] B. Dachwald, H. Boehnhardt, U. Broj, U.R.M.E. Geppert, J.T. Grundmann, W. Seboldt, P. Seefeldt, P. Spietz, L. Johnson, E. Kührt, S. Mottola, M. Macdonald, C.R. McInnes, M. Vasile, R. Reinhard, Gossamer Roadmap Technology Reference Study for a Multiple NEO Rendezvous Mission, Advances in Solar Sailing, Springer Praxis 2014, pp 211-226. – *also*: A. Peloni, M. Ceriotti, B. Dachwald, Solar-Sail Trajectory Design for a Multiple Near-Earth-Asteroid Rendezvous Mission, Journal of Guidance, Control, and Dynamics, 2016, DOI: 10.2514/1.G000470 .

[28] P. Seefeldt, T. Spröwitz, J.T. Grundmann, Verification Testing of the GOSSAMER-1 Deployment Demonstrator, IAC-2016-C2.2.3 – *also*: P. Seefeldt, T. Spröwitz, Qualification Testing of the Gossamer-1 Deployment Technology, ECSSMET 2016, #56220 (*in preparation*).

[29] Seefeldt, P., Spietz, P., Sproewitz, T., Grundmann, J.T., Hillebrandt, M., Hobbie, C., Ruffer, M., Straubel, M., Tóth, N., Zander, M., Gossamer-1: Mission Concept and Technology for a Controlled Deployment of Gossamer Spacecraft, Advances in Space Research (2016), doi: http://dx.doi.org/10.1016/j.asr.2016.09.022.

[30] NASA GSFC, Preliminary Mission Report Spartan 207/Inflatable Antenna Experiment Flown on STS-77, Spartan Project Code 740.1, 1997, http://www.lgarde.com/assets/content/files/publications/207.pdf.

[31] O. Mori, H. Sawada, R. Funase, T. Endo, M. Morimoto, T. Yamamoto, Y. Tsuda, Y. Kawakatsu, J. Kawaguchi, Development of First Solar Power Sail Demonstrator – IKAROS.

[32] O. Mori, Y. Shirasawa, H. Sawada, Y. Mimasu, Y. Tsuda, R. Funase, T. Saiki, T. Yamamoto, N. Motooka, Y. Kishino, J. Kawaguchi, IKAROS Extended Mission and Advanced Solar Power Sail Mission, 63rd IAC 2012, IAC-12,D1,1,3,x15786.

[33] Michael F. Piszczor Piszczor, Scott W. Benson, David A., Scheiman Scheiman, Homer J. Fincannon, Steven R. Oleson, Geoffrey A. Landis, Advanced Solar Cell and Array Technology for NASA Deep Space Missions, 33rd Photovoltaic Specialists Conference, 2008.

[34] P. Seefeldt, W. Bauer, B. Dachwald, J.T. rundmann, M. Straubel, M. Sznajder, N. Tóth, M.E. Zander, Large Lightweight Deployable Structures for Planetary Defence: Solar Sail Propulsion, Solar Concentrator Payloads, Large-Scale Photovoltaic Power, 4th IAA Planetary Defense Conference – PDC 2015, IAA-PDC-15-P-20.

[35] S. Kawakita, M. Imaizumi, T. Sumita, K. Kushiya, T. Ohshima, M. Yamaguchi, S. Matsuda, S. Yoda, T. Kamiya, Super Radiation Tolerance of CIGS Solar Cells Demonstrated in Space by MDS-1 Satellite, 3rd World Conference on Photovoltaic Energy Conversion, 2003, Osaka, 3P-B5-11

[36] http://global.jaxa.jp/activity/pr/brochure/files/sat11.pdf

[37] Y. Kimoto, H. Koshiishi, H. Matsumoto, T. Goka, Total Dose Orbital Data by Dosimeter Onboard Tsubasa (MDS-1) Satellite, IEEE Transactions on Nuclear Science, Vol. 50, No. 6, December 2003.

[38] Frank Dannemann, Michael Jetzschmann, Technology-driven Design of a Scalable Small Satellite Platform, 4S Symposium 2016.

[39] Christian Grimm, Jan Thimo Grundmann, Jeffrey Hendrikse, Nawarat Termtanasombat, Christian Ziach, Going Beyond the Possible, Going Beyond the “Standard” of Spacecraft Integration and Testing!, 30th ISTS, 2015.

[40] C.D. Grimm, J.T. Grundmann, J. Hendrikse, On Time, On Target – How the Small Asteroid Lander MASCOT Caught a Ride Aboard HAYABUSA-2 in 3 Years, 1 Week and 48 Hours, 4th IAA Planetary Defense Conference – PDC 2015, IAA-PDC-15-P-66.

[41] Caroline Lange, Ross Findlay, Christian Grimm, Jan Thimo Grundmann, Tra-Mi Ho, Lars Witte, Tim van Zoest, “How to build a 10 kg autonomous Asteroid landing package with 3 kg of instruments in 6 years?” – System Engineering challenges of a high-density deep space system in the DLR MASCOT project, SECESA 2012.

[42] C. Lange, J.T. Grundmann, J. Hendrikse, M. Lange, N. Tóth, Technology and knowledge reuse concepts to enable responsive NEO characterization missions based on the MASCOT lander, 4th IAA Planetary Defense Conference – PDC 2015, IAA-PDC-15-P-65.

[43] C. Lange, J.T. Grundmann, M. Kretzenbacher, P.M. Fischer, Systematic Reuse and Platforming – Case Studies for Enhancing Reuse with Model Based System Engineering Methods In Space Systems Development, 7th International Conference on Systems & Concurrent Engineering for Space Applications (SECESA) 2016 (*in preparation*)