QUALIFICATION TESTING OF THE GOSSAMER-1 DEPLOYMENT TECHNOLOGY

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ABSTRACT

Gossamer structures for innovative space applications, such as solar sails, require a technology that allows their controlled and thereby safe deployment. Before employing such technology for a dedicated science mission, it is necessary, to demonstrate its reliability with a Technology Readiness Level of six or higher.

The aim of the presented work is to provide a reliable technology that enables the controlled deployment and verification of its functionality with various laboratory tests to qualify the hardware for a first demonstration in low Earth orbit. The development was made in the Gossamer-1 project of the German Aerospace Center.

This presentation provides an overview of the Gossamer-1 hardware development. The design is based on a crossed boom configuration with triangular sail segments. Employing engineering models, all aspects of the deployment were tested under ambient environment. Several components were also subjected to environmental qualification testing.

An innovative stowing and deployment strategy for a controlled deployment and the required mechanisms are described. The tests conducted provide insight into the deployment process and allow a mechanical characterization of this process, in particular the measurement of the deployment forces.

Deployment on system level could partially be demonstrated to be robust and controllable. The deployment technology is on Technology Readiness Level four approaching level five, with an engineering qualification model (EQM) for environmental testing currently being tested.

1. INTRODUCTION

In the last years, the DLR (German Aerospace Center) has pursued the development of a scalable deployment technology for gossamer spacecraft systems, suitable for autonomous and controlled deployment. A summary of those developments is given in this paper. While the focus was on solar sails and thin-film photovoltaics, the aim of the development is to provide a scalable technology for deployable membranes for various space applications. The development was made within the DLR project Gossamer-1. It was initiated with the goal of developing the required deployment technology and its demonstration in LEO (Low Earth Orbit) by means of a scaled demonstrator as shown in Figure 1.

The development of solar sail technologies in Europe and at DLR goes back to the 1990s when the first solar sail breadboards were tested using a 20 m x 20 m sail in a joint DLR, NASA/JPL and ESA project, followed by development projects like ODISSEE [1] and GEOSAIL [2]. The ground demonstration is presented by Leipold in [3] and the study activities are summarized in [4].

Gossamer-1 employs the knowledge gained from these projects and reuses the previously developed CFRP (Carbonfiber Reinforced Plastic) booms, as well as state of the art aluminum coated polyimide foil. With respect to the deployment and the evolved mechanisms, it was recognized that previous strategies had disadvantages with respect to controlling and automatizing the deployment. In addition, previous projects aimed for the realization of a complete solar sail mission with a scientific payload. This increased mission complexity and cost. Ultimately, the earlier projects were not able to realize a full mission. In consequence, a step-wise development focusing on the deployment technology was pursued starting with Gossamer-1. It is a low cost technology demonstrator as part of an intended three-step scalable technology development covering membranes, booms, photovoltaics and their corresponding mechanisms. Scalable means that Gossamer-1 is a 5 m x 5 m technology demonstrator using technology that is suited to build Gossamer-2 with 25 m x 25 m and Gossamer-3 with 50 m x 50 m.

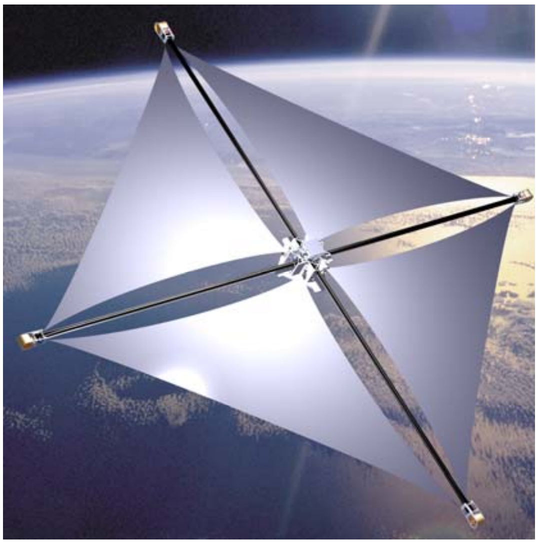


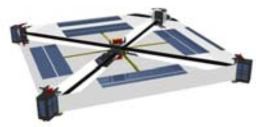
Fig. 1. Gossamer-1 demonstrator, artist’s rendering

Gossamer-1 is based on a crossed boom configuration with four sail segments. At the geometric center of the spacecraft, the booms' crossing point, the Central Spacecraft Unit (CSCU) carries the satellite's main bus system, including all electronics covering command and data handling, power system, as well as ground communications system. Four Boom and Sail Deployment Units (BSDUs) are mounted on the booms, one on each boom. In the stowed configuration, they are mechanically locked and electrically (power and data) connected to the central unit. For deployment, the deployment units are unlocked and disconnected from the central unit and move outward, thereby simultaneously deploying the booms and the sail segments. During deployment, communication with the central unit is achieved via a wireless on-board communications system. Each BSDU has its own power system and on-board computer, as there are no wired connections foreseen in the booms. By this, a controlled and automatized deployment is realized that contrasts to the achievements of other projects like JAXA's IKAROS (see [5]) and NASA's NanoSail-D (see [6]). The deployment process is monitored by analyzing various characteristics and can be stopped and resumed at any time, if required.

The satellite has an estimated mass of about 30 kg and the compact launch configuration shown in Figure 2(a) has a maximum width of approximately 790 mm and a height of 500 mm. Figure 3 provides an overview of the system components. It was planned to launch the Gossamer-1 satellite as secondary payload within the EC FP7 Project QB50 [7]. However, due to prioritization of other competing projects, it was not possible to build the complete satellite and as a consequence the launch opportunity with QB50 could not be used. Achieved were the design of a technology demonstration mission and the development of a new deployment strategy that meets the above stated goals. Engineering models of all hardware were built and subject to various tests.

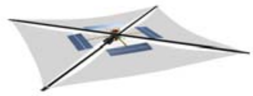
The deployment technology is described in the following section. The tests conducted with the engineering models of the deployment technology are presented in Section 3. The tests show the functionality of the Gossamer-1 deployment technology, including mechanisms and electronics.

(a) Launch Configuration



(b) During deployment

(c) Deployed



(d) Deployed with jettisoned mechanisms

Fig. 2. Gossamer-1 deployment sequence

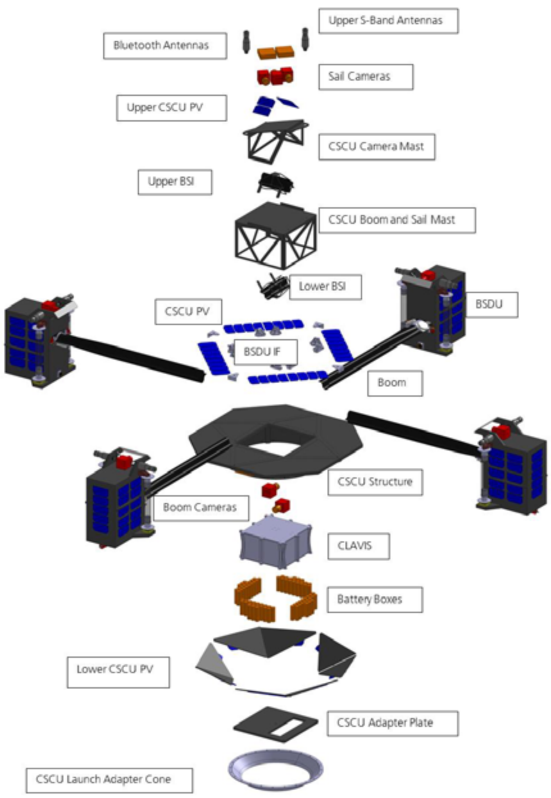


Fig. 3. Gossamer-1 exploded view

2. BOOM AND SAIL TECHNOLOGY

In the following paragraphs, the subcomponents and mechanisms enabling the deployment will be described in further detail.

2.1 BOOMS

Gossamer-1 makes use of light-weight coilable CFRP booms, also referred to as collapsible tube masts, as shown in Figure 4(a). Two booms are configured in a cross-like arrangement with a vertical displacement. The booms are mounted to the CSCU via a Boom-Spacecraft Interface (BSI) as shown in Figure 4(b).

DLR previously developed and investigated the technology in precursor projects, e.g. ODISSEE [1] and Geosail [2]. The cross section of the boom was chosen according to the smallest possible dimensions that allow coiling of the boom without reaching critical stress levels in the material and adhesive layers. The length of one full-diagonal boom is 8.6 m. It is determined by the chosen sail size of 5 m x 5 m and the necessary remaining length for the jettisoning of the BSDUs.
During the deployment, the boom cross section is not constant along the boom. The diameter increases in y-direction along the deployed length, starting with the flat configuration at the point where the boom is coiled inside the BSDU (see Figure 4(a)). It takes more than one meter until the boom's cross section in y-direction is comparable to the deployed configuration and a small distortion of the cross section can be observed along the whole boom length. Due to the reduced geometrical moments of inertia, respectively bending stiffness, the boom section closest to the boom hub at which the boom is uncoiled is most sensitive to mechanical loads and therefore requires a linear guiding.

(a) Partially stowed boom with larger cross section compared to Gossamer-1

(b) Boom S/C Interface for two crossed booms with vertical displacement

Fig. 4. Coilable thin shell CFRP booms and interfaces

2.2 SAILS

A preliminary material selection was presented by Seefeldt [8]. For the sail membranes, the 7.5 µm thick polyimide foil Upilex-S® covered on both sides with 100 nm vacuum deposited aluminum was chosen. It is delivered on a roll of a width of 1.016 mm. Additionally, samples were coated with silicon oxide on top of the aluminum to increase the infrared emittance which is still under investigation. The sails are manufactured by using 3M® transfer adhesive tape 966. First, five sheets are prepared, one with the photovoltaics. By bonding the edges with the transfer adhesive after folding them over, a reinforcement against cracks is achieved. The adhesive tape is also used to mount interfaces and attach the photovoltaics with its harness. In a final step all segments are bonded together in order to achieve the required sail size.
Within the Geosail precursor project [2], the transfer adhesive was tested for low temperatures down to -142 °C. In addition to that work, a short term duration test in a furnace was conducted, reaching temperatures up to 230 °C. In these tests, the adhesive bonding was loaded with 0.9 N/cm² (shear) and withstood the high temperature. The loading was roughly twice as high as the limit specified in the data sheet. In contrast to the design presented by Seefeldt [8], a rigging is no longer used in the present design. Instead, the interface points are reinforced with a thicker copper coated foil, similar to what is used for flexible PCBs (Printed Circuit Boards). The connection between those reinforced interfaces and the interface to the boom and the CSCU are made of a 0.45 mm stainless steel ropes.
The stowing strategy is shown in Figure 5. The triangular segments are folded in a zig-zag pattern and coiled onto two spools. The spools are mounted on two neighboring BSDUs (see Figure 2(a)). Folding and coiling the sail this way is a key for controlled deployment. During sail deployment, only the minimal required amount of sail is uncoiled from the sail spools the deployed sail is always under tension. The stowing strategy was subject to intensive testing, presented by Seefeldt [9]. The tests are summarized in Section 3.

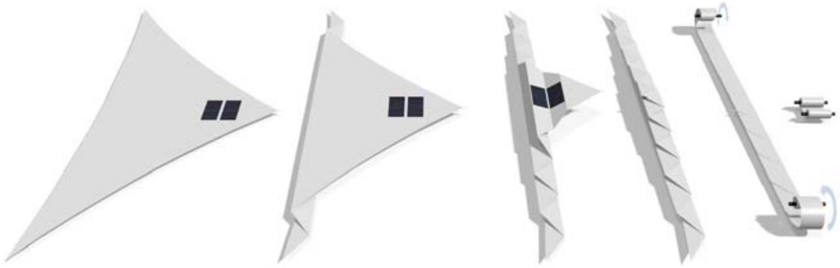


Fig. 5. Gossamer-1 sail stowing strategy for one of the four segments

The photovoltaic part of the prototype sail is shown in Figure 6. The thin-film photovoltaics are located at the inner corner, close to the CSCU. These consist of small experimental modules that are bonded to the sails employing the abovementioned transfer adhesive. The modules are electrically contacted to a flexible PCB harness in the middle of the triangle. Note that the modules are currently experimental prototypes that are the subject of ongoing studies.

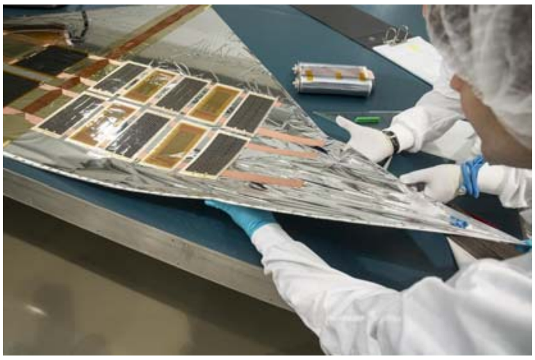


Fig. 6. Thin-film photovoltaic integrated on the sail foil

2.3 BOOM AND SAIL DEPLOYMENT MECHANISMS

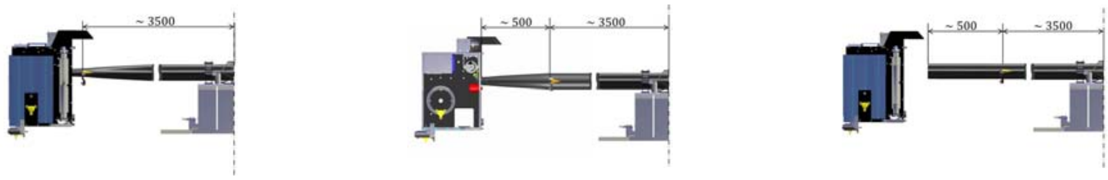
As already mentioned, the deployment is driven by BSDUs that are moving away from the CSCU. Booms and sail segments are thereby deployed at the same time. Figure 7 shows one BSDU (without the sails) during the whole deployment process. The engineering model of the boom deployment mechanism was also presented by Straubel [10].

In the stowed configuration (see Figure 7(a)) launch locks secure the BSDU onto the CSCU which are released prior to deployment. The deployment is driven by a belt which is coiled on the boom hub together with the boom. At the very end of the boom, a small piece of Velcro connects the belt to the boom. The boom and consequently the sails are deployed by pulling-off the belt from the boom hub and thereby uncoiling the boom. As the boom deploys it pushes the BSDU away from the CSCU, which in turn uncoils the sail segments from the sail spools. The transferred shear load is well supported by the Velcro and the compression loads between the coiled layers also prevent premature separation of both Velcro parts by pressing both components together.

The uncoiling of the belt is driven by the belt winding mechanism (BWM) using an electric motor. To prevent uncontrolled deployment of the booms and sails, e.g. by stored elastic energy, the boom hub and the sail spools have brake mechanisms as described in the following dedicated paragraphs.

To achieve the jettisoning function of the BSDU, the Boom Sail Fixation Ring (BSFR) provides the interface between the outer sail corners and the boom. During sail deployment, the BSFR is attached to the BSDU with the boom running through the ring-like shape of the BSFR. Once the sail is fully deployed (Figure 7(c)), the BSFR is locked to the boom and mechanically separated from the BSDU (Figure 7(d)). At this point the BWM drive unit can be engaged again to further deploy the remaining boom for a complete jettisoning (Figure 7(e) and 7(f)). At this final stage of the deployment, the tip of the boom is deployed by transferring the deployment load purely through the Velcro. As the Velcro passes the pulley and the Velcro loading transforms from shear loading into peel loading both parts are separated without a decisive deceleration of the BSDU. The BSDU and boom are separated completely, and the BSDU maintains the previously gained kinetic energy and floats away as indicated by Figure 7(f).

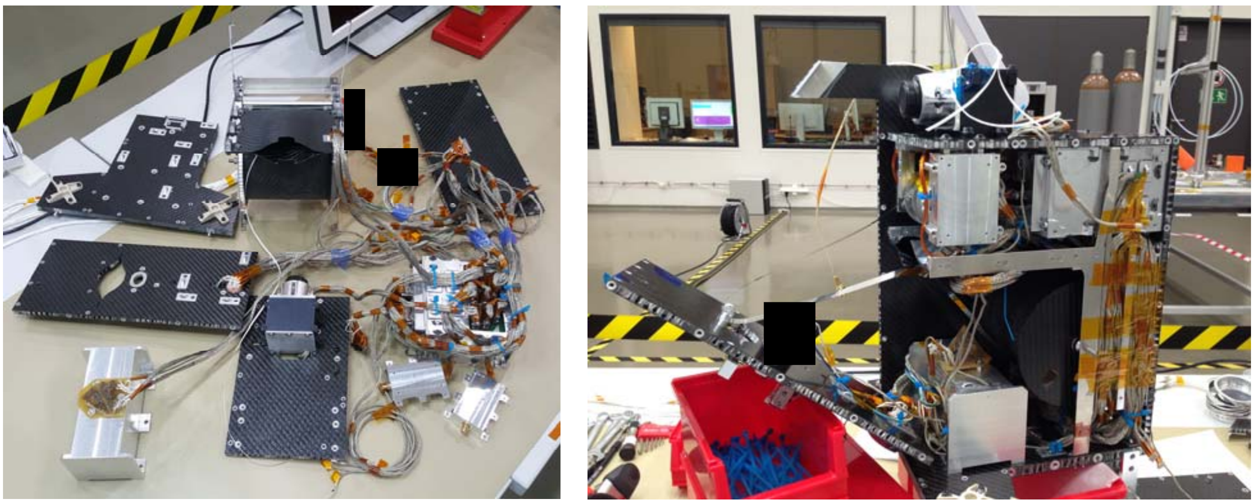
(a) Launch Configuration
(b) BSDU is released and deployment started; the belt (green) is coiled by BWM
(c) Sails fully deployed; BSFR is locked by tape spring on boom



(d) BSFR separated and remaining boom is deployed
(e) Belt connected by Velcro is separated from boom
(f) BSDU is jettisoned and drifts away

Fig. 7. BSDU deployment sequence. For clear repre-sentation, one BSDU without sail segments is shown

The EQM of the BSDU features all mechanisms, structural elements, mechanisms and actuators as well as membranes, avionics, wireless communication and sensoring. Mechanisms, launch locks and sensoring are described in more detail in the following subsections. Figure 8 gives an impression on the component density inside the BSDU, which is in itself a complete space system.



(a) EQM BSDU in exploded view
(b) EQM BSDU during final integration

Fig. 8. BSDU EQM hardware during integration for system level testing (ITAR elements blacked out)

Belt Winding Mechanism

As explained above, the BWM pulls off a 0.03 mm thick stainless steel belt that is coiled onto the Boom Hub together with the boom. The BWM consists of an electrical motor, a belt spool with a diameter of 40 mm, and a freewheel to ensure that the belt is always under tension. The winding spool is directly mounted on the output shaft of the gearbox employing a feather key. The freewheel is made of a gear with pitched teeth that is part of the winding spool and an engaging copper beryllium spring plate (blue part). The belt is guided by a diverting pulley to the BWM spool.

The motor of the winding mechanism has to overcome torques induced by the boom hub, the boom guidance and the sail spool. A critical point is that motors used under vacuum conditions easily overheat. As a consequence, the resulting life cycle needs to be critically evaluated. During deployment the motor has to run at low speed for a relatively long time. After a longer break for cooling down the motors during jettisoning will take place with high motor speed for a short period. The Phytron VSS32 motor with a GPL32 gear box was chosen for the engineering model. For the EQM, the company produced a customized Version of the VSS32 motor with a GPL22 gear box. In order to withstand the high mechanical launch loads, the design of motor and gearbox was made more robust. That led to a slight increase in size, which was compensated by the smaller GPL22 so that it still fits into the dedicated space inside the BSDU. The change in the gear box led to a change in the transmission ratio from 50:1 to 49:1. Under vacuum, the motor can run 6 rpm up to 7.5 min for deployment, and 30 rpm up to 1 min for jettison until it overheats. Considering the spool diameter of 40 mm, the corresponding deployment speeds are 1.3×10^{-2} m/s for the slower mode and 6.3×10^{-2} m/s for the faster. It is desirable to use the slowest deployment speed possible in order to reduce inertial loads during deployment. In order to deploy the boom to 3.8 m, the locking point of the BSFR, in the maximum motor operating time for slower speeds of 7.5 min, the deployment speed is determined to be 0.84×10^{-2} m/s. A torque budget, derived from force measurements with the engineering models, is given in Section 3.2.

Boom Hub

The boom hub is a rotatable mounted spool on which boom and belt are coiled. It is mounted with a plain bearing. The design is presented in Figure 9. On one side of the boom hub there is a gear with additional conical holes. For launch, the rotation of the spool is locked by a conical pin that locks into the holes on the side of the gear. A pin puller (highlighted in yellow) releases the gear rotation in orbit.

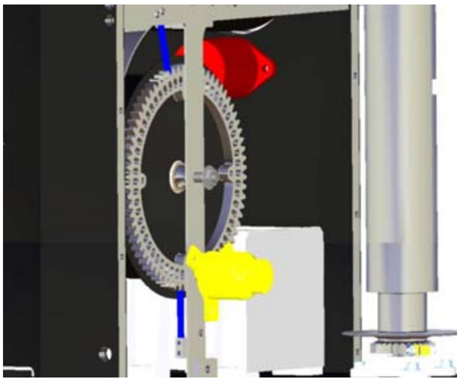


Fig. 9. Boom hub with gear and leafe springs (blue). The pin –puller (yellow) lock into the holes of the gear

In order to have a controlled deployment that can be stopped and resumed at any time, and to counteract the self-deployment of the boom due to stored elastic energy, the boom hub includes the aforementioned brake mechanism. It employs copper-beryllium plates (highlighted blue) that engage into the gear. Through the deformation of those leaf springs when rotating the hub, an oscillating torque with a maximum of about 0.25 Nm is generated.

Boom Sail Fixation Ring

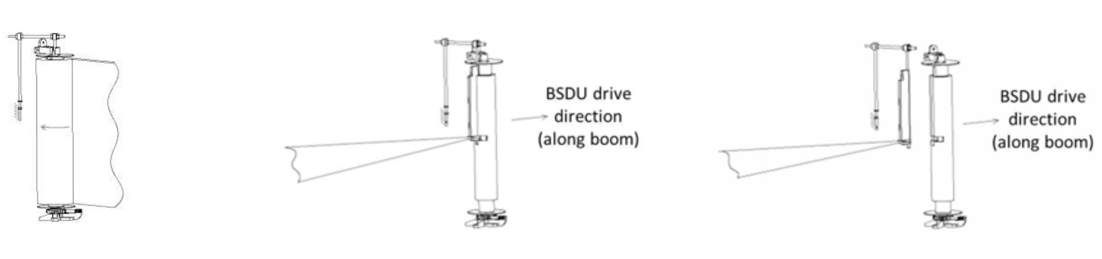
The Boom Sail Fixation Ring is the boom-sail interface. During deployment the boom slides through the BSFR. At the point where the sails are fully deployed, the sails must be mounted to the booms. This is achieved by attaching the BSFR at this position to the boom by employing tape springs that are glued onto the boom. During deployment, the BSDU with the BSFR moves across the tape spring until the BSFR locks in right behind the spring.

After the ring is locked into its final position, the separation (Phase 5) between BSFR and BSDU takes place. This is achieved by employing the Ejection and Release Mechanism (ERM) E250 STD from TiNi Aerospace Inc. It opens the mounting between BSFR and the BSDU. Afterwards the BSDU can move further, deploying the last centimeters of the booms leaving the BSFR with the mounted sail at the fixation point.

Sail Spools

Each of the four sail quadrants is folded and coiled onto two sail spools, which are mounted on two adjacent BSDUs. When uncoiling the sail segment, the spool with the sail interface rotates around the truss-like structure connected to the BSFR (Figure 10(a)). After the sail segment is uncoiled, the truss-like structure directly mounts the sail through the sail interface to the BSFR (Figure 10(b)). After the separation from the BSFR the BSDU with the sail spools drives further along the booms, thereby separating the sail spool from the truss like structure that is mounting the sail to the BSFR (Figure 10(c)). The patent of Seefeldt and Spietz [13] can be reviewed for details of the mechanism function.

During launch, a gear wheel on the sail spool bottom side is used to lock the spool with a corresponding counterpart mounted on the CSCU. A leaf spring engaging the gear adds an oscillating break torque of approximately 0.035 Nm at maximum. This is required during deployment to ensure that the sail does not slip off of the spool. The mechanism allows a complete stop within the deployment process and still has the partly-deployed sail safely mounted.



(a) Sail Segment uncoiling (b) Segment uncoiled with interface to truss structure (c) Separated truss structure

Fig. 10. Sail separation sequence

Launch Locks

During launch, all mechanisms are locked in order to provide a mechanically stable configuration of all parts. An overview of the locking mechanisms employed is provided in Figure 11.

The Boom Hub is locked by a P5 pin puller from TiNi Aerospace, Inc. It is mounted on the outer wall of the BSDU, and the pin is locked into one of the conical holes located around the boom hub gearwheel. In order to simplify the integration, 60 holes allow the hub to be locked in the necessary position. A cone shape for the pin and the holes was chosen in order to avoid clamping of the locked pin (e.g. due to thermal expansion).

Additionally, a form-fitting locking element ensures the locking of each sail spool by engaging its gear and a circumferential groove in the sail spool's lower end (see Figure 11 on the right).

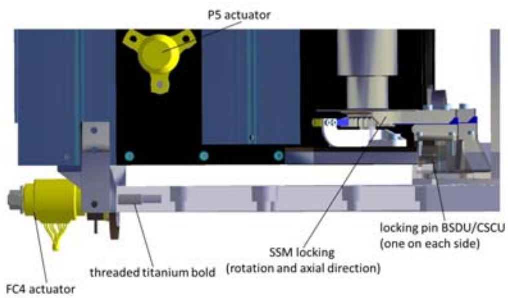


Fig. 11. BSDU Launch Locks

2.4. DEPLOYMENT MONITORING

An in-orbit demonstration of the deployment technology requires sensors to gather data for the system validation. Therefore, a boom length measurement, a camera system and a measurement of the boom loading using strain gauges was implemented.

Boom length measurement

Strips with reflective markers attached to the boom flanges (see Figure 12) are used to determine the position based on counts of changes in reflectivity with an optoelectronic sensor. Implementing periodically occurring calibration markers and a slight phase shift in the pattern provides higher robustness of position determination.

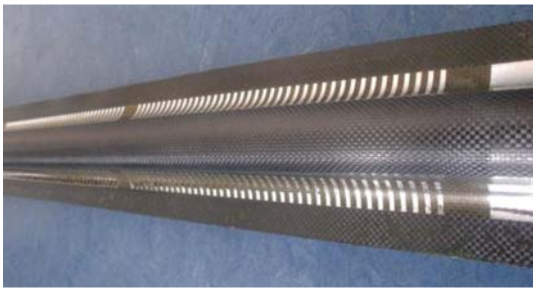


Fig. 12. Reflective marker on the boom

Camera System for Visual Documentation

The camera system consists of 9 cameras with differing focal length. One camera is placed on top of each deployment unit facing inwards and covering the full spacecraft by wide field optics. Three cameras on the central unit facing outwards with wide field optics, covering one sail segment, adjacent booms and deployment units. Two of these are positioned such that stereoscopic viewing is supported. The two remaining cameras on the central unit cover one boom and its deployment unit with a depth of field ranging from roughly the initial unlocking up to the final position.

Boom loading measurement

Boom loads are determined by strain gauges attached to the booms near the BSI. Besides general monitoring for an on-orbit characterization of the deployment system, they are also used to detect boom overload, which would trigger an emergency stop and additional FDIR (Fault Detection, Isolation and Recovery). Zander [12] presented preliminary experiments for future in-orbit load and deflection monitoring.

3. DEPLOYMENT TECHNOLOGY TESTING

In order to validate the technology, a series of development as well as qualification tests were performed using different engineering models. The tests ranged from mechanical characterization of booms, sail manufacturing and sail folding techniques, to characterization and functional testing of individual mechanisms. A full two-segment system level deployment test under ambient conditions using an engineering model of the BSDU was conducted. Qualification testing of one deployment unit with boom and adjacent sail segments is carried out with the flight representative EQM model. This also includes all electronic subsystems contained in the deployment unit.

3.1 SAIL TESTING

Pre-qualification tests were performed with a mechanically flight representative sail packed according to Figure 5 and stowed on two sail spool engineering models. Thin film photovoltaics were simulated by mechanically representative dummies made from flexible PCB material. Harnessing on the sail was accomplished using loosely bundled high-quality industrial PTFE-insulated AWG28 litz wire. The wire type used was previously qualified at system level for

MASCOT (see [11]). Following a test-as-you-fly philosophy test were performed starting with a shaker test followed by centrifugal acceleration, fast decompression, and finally deployment under ambient conditions (see Deployment Testing of this Section). The tests were also presented by Seefeldt in [9]. Test loads were based on the launcher load envelope.
All tests except the deployment were conducted with a test adapter specially designed for those tests as shown in Figure 13(a). It has a representative bearing and locking mechanism for the spools included. For final functional verification, the sail package and sail spools were transferred to the deployment test rig (see Figure 13(b)). To deploy one sail segment two linear drives of 4.5 m length at a right angle were used. The sail spools were mounted on these units with tri-axial force sensors placed between linear drives and sail spools. The deployment was realized be a computer controlled movement of the linear drives. Different deployment speeds and speed profiles could be tested. The Sail package and sail spools passed the test successfully with no anomalies observed.

(a) Sail package mounted on test adapter

(b) Deployment test of one sail segment alone without booms and BSDU

Fig. 13. Sail Spool test adapter and Sail deployment test rig

3.2 ENGINEERING MODEL DEPLOYMENT TESTING

Laboratory deployment tests were made at different levels of complexity, starting with individual subsystems up to final full functional system level tests. The goal was the verification of:

- the general deployment strategy,
- sail stowing and deployment,
- boom stowing and deployment,
- related force budgets,
- mechanism functionality,
- the electronics involved (position determination, camera system, on-board wireless communications),
- the deployment logic implemented.

Boom stowing and boom deployment was tested in so-called boom-pull out tests with just a single boom and a mechanically functional representative BSDU. No sails or sail deployment simulators were applied. Oscillations caused by the leaf spring of the boom hub brake mechanism as well as imperfections and inhomogeneity of the material were observed. Values vary between 5 to 15 N with an approximate average of about 10 N. The results were presented by Straubel in [17].
The test rig, which was used for the sail testing, was extended for the deployment of two sail segments with one boom and one BSDU for system level deployment tests. It consists of two linear drives arranged in a line simulating one full boom diagonal of a Gossamer-1 configuration (see Figure 14). This test setup enables a fully functional system level test including mechanisms, electronics and implemented logic.
One boom and BSDU can be tested at right angles between the linear drives (Figure14). The boom was mounted to a BSI and was deployed by a fully functional BSDU engineering model. The BSDU was supported by a test rig, with air bearings for minimum friction in order to allow free

BSDU and boom movement within the sail plane. On each linear drive, a sail spool was mounted on top of a tri-axial force sensor. The BSDU was fully equipped including the sail spools on both sides. This setup allowed for the deployment of one boom and both adjacent sail segments and is referred to as one-boom-two-sail-segment system level test. The BSDU was controlled by the on-board wireless communications with a fully functional CSCU electronics system including EGSE and suitable control interfaces. Acquisition of sensor data as well as BSDU camera images was implemented. The data was transferred via the on-board wireless communications system from the BSDU to the CSCU.

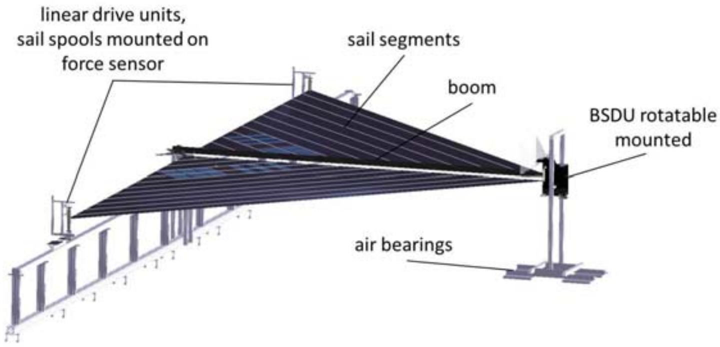


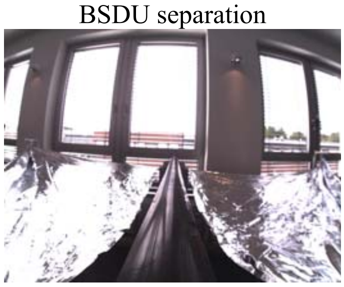
Fig. 14. Test rig for the deployment of two sail segments with one boom and BSDU

Different phases of the deployment test are shown in Figure 15. The deployment is shown in Figure 15(a), followed by the separation Figure 15(b) and the BSDU jettison in Figure 15(c). Figure 15(d) shows an image acquired by the BSDU on-board camera during a deployment test.

(a) Deployment and acquisition of picture with on board camera

(b) Sail completely deployed, BSDU separation

(c) BSDU jettison



(d) On-board camera picture during deployment

Fig. 15. Gossamer-1 deployment test in progress

The same way as for boom pull-out, the sail spools and sail deployment also introduce forces when pulling off the sail from the sail spool. These forces were measured during deployment by force sensors placed between the linear drive units and the corresponding sail spool mount. Data was recorded as a function of time. Maximum values were observed with 2.2 N. This applies to one sail spool. As one BSDU has to pull off two sail halves, this force must be considered twice in the budget, resulting in 4.4 N.
Similar to the boom pull-out, the sail pull-off measurements also showed a fast oscillation caused by the leaf spring brakes at the sail spools. The oscillations are roughly about 1.3 N. Besides a smaller amount of friction between the tip of the spring and the gear, this mainly represents the

deformation of the spring. There is a general trend of increasing forces during the sail deployment due to two main effects. The diameter of the sail coiled on the spool is decreasing from about 50 mm at the beginning to the spool diameter of 35 mm at the end. This leads to a force increase of about 0.4 N. Additionally, the deployed sail introduces tension forces when deployed in the laboratory under gravitation. The highest forces appear at the point shortly before the sail is completely deployed and when jettisoning the BSDU. At both times the force is about 2.2 N. Figure 16 shows the measured contributions to the full force budget.

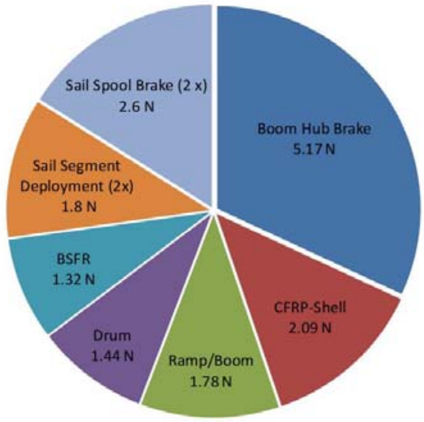


Fig. 16. Composition of the deployment force that is introduced through the BWM

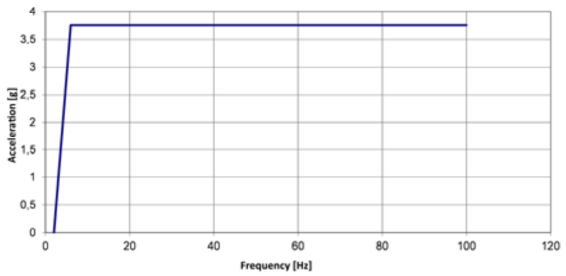
Forces purposely added by the sail spool and boom hub leaf spring brake add up to 5.2 N + 2.6 N = 7.8 N, whereas the major friction related contributions of the boom deployment add up to 6.6 N. In addition, the laboratory sail deployment introduces forces of 1.8 N. This is mainly gravitation related, but also includes an unknown fraction of friction force of the sail spool mechanisms. These forces transform into the required drive torque at the gear's axis through multiplication with the radius of the belt winding mechanism's spool of 20 mm. The torques were multiplied with uncertainty and safety factors according to ECSS-E-ST-01C [18] and sum up to 0.86 Nm.

3.3 SYSTEM LEVEL TESTING

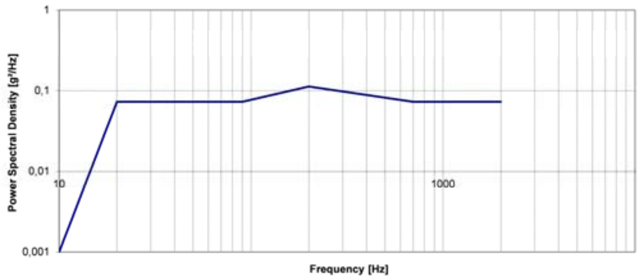
System level tests are performed using the flightlike EQM of the deployment system consisting of one BSDU, one Boom and two sail segments partially equipped with photovoltaic or representative dummies. Aim of the tests is reaching TRL 5 for the main technologies by testing under representative environmental conditions. The integration of the complete EQM and the sail manufacturing were performed in the ISO 8 integration hall of the DLR Institute of Space Systems. All system level tests were also performed in ISO 8 environment serving as good practical experience for the integration and testing of future deployment systems.
As already mentioned the test sequence was chosen according to the test-as-you-fly philosophy starting with vibration testing, followed by venting testing and thermal-vacuum testing including a partial deployment in vacuum at low and high temperatures. The sequence will be concluded with a laboratory full deployment test in the ISO 8 integration hall.

Vibration Testing

Vibration testing was performed on the 11 kN shaker of the institute in ISO 8 environment. The sinusoidal and random vibration loads as shown in Figure 17 are an envelop of the loads of the most probable launchers and are applied to all three test axes. No amplifications were taken into account. The main body of Gossamer-1, the CSCU, was considered to be a stiff body. Figure 18(a) shows the test setup for the vertical testing of the EQM BSDU with integrated sails on the test adpater.



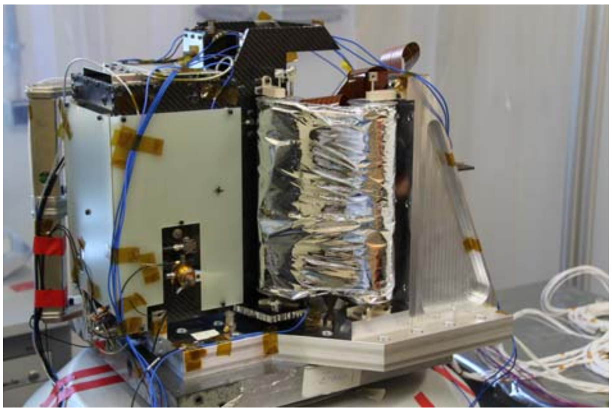
(a) sinusoidal testing



(b) random testing

Fig. 17. Load profiles for the vibration testing

The tests did neither yield structural damages nor did they show frequency shifts larger than 5% between the different test runs. All functional tests during and after the vibration tests were successful.



(a) EQM BSDU mounted on Vibration Shaker

(b) EQM Venting test configuration

Fig. 18. Shaker and venting test setup for EQM system level test

Even though the requested eigenfrequency design criterion with ≥100 Hz could not be fulfilled the analysis and the experimental results show a relatively good agreement as can be seen in Table 1. However, for a better judgement a thourough investigation on the mode shapes needs to be performed.

Tab. 1. Comparison of numerical and experimental eigenfrequencies

# of Eigenfrequency	Analysis	Experimental
1	76 Hz	60 Hz
2	83 Hz	75 Hz
3	230 Hz	237 Hz

Venting Testing

Vibration testing is followed by the venting testing. For that purpose the EQM BSDU is placed in a 0.3 m³ test chamber with ambient pressure. This small chamber is connected to the evacuated 17 m³ Space Simulation Chamber of the insitute as shown in Figure 18(b). By a determined opening of the valve between both chambers the small chamber is rapidly evacuted. Especially for the folded and rolled membrane this load case can be decisive if air is trapped between folds of the sail.

Figure 19 shows the depressurization curve with maximum pressure differences of up to 70 mbar/sec and reaching a pressure of less than 50 mbar within 45 sec. This is compliant with a large number of launcher ascent profiles.

Post test inspections did not reveal any changes or damages on the sail package. A post test functional test of the unit did prove full operability after the test.

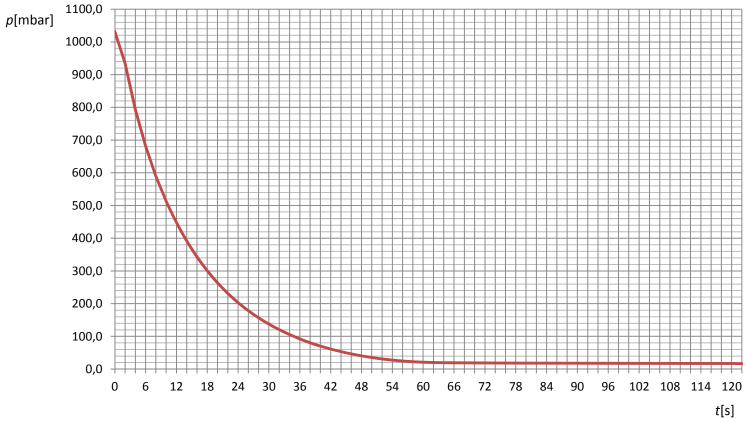


Fig. 19. Depressurization curve

<u>Thermal Vacuum Testing and Partial Deployment</u>

At the time of writing this paper the EQM BSDU was currently being tested. Figure 20 shows the EQM BSDU in its configuration for the thermal vacuum testing. The BSDU itself is placed on a carriage in order to be able to deploy the BSDU for some millimeters after successful actuation of all release mechanisms.

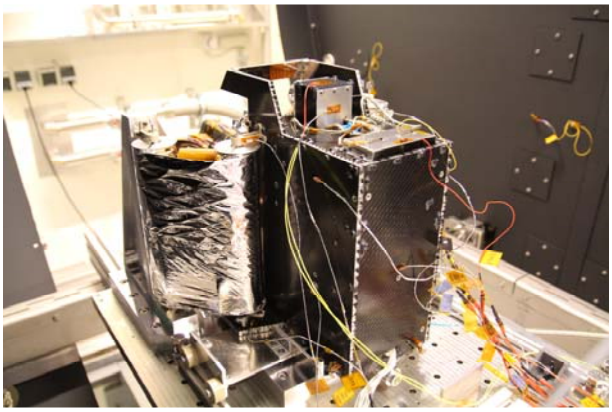


Fig. 20. Thermal vacuum EQM system level test with movable BSDU for separation testing

The test scenario is shown in Figure 21 and resembles a cycling test of 4 cycles which forsees the actuation of all release mechanisms and a partial deployment in the cold phase of the third cycle. Another partial deployment is foreseen in the hot case of the last cycle. Hot operating temperature is defined at 50 °C and cold operating temperature at -40 °C with the motor as temperature reference point.

Currently the EQM is in its second cycle. All functional tests performed yet did not yield any anomalies in the operation of the BSDU.

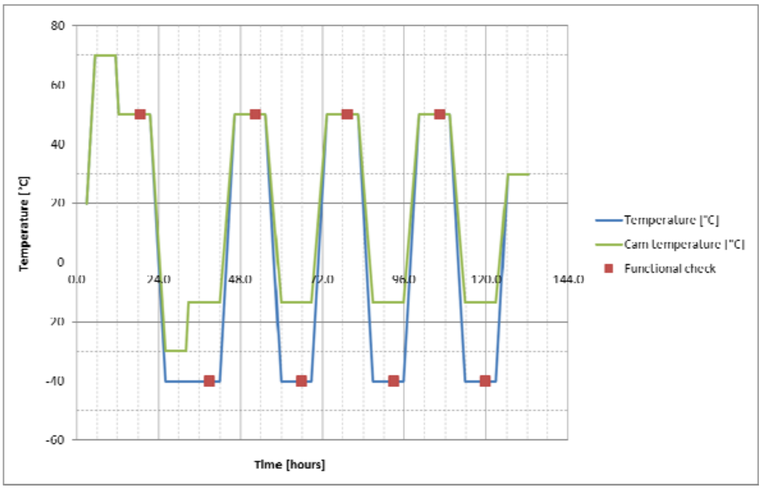
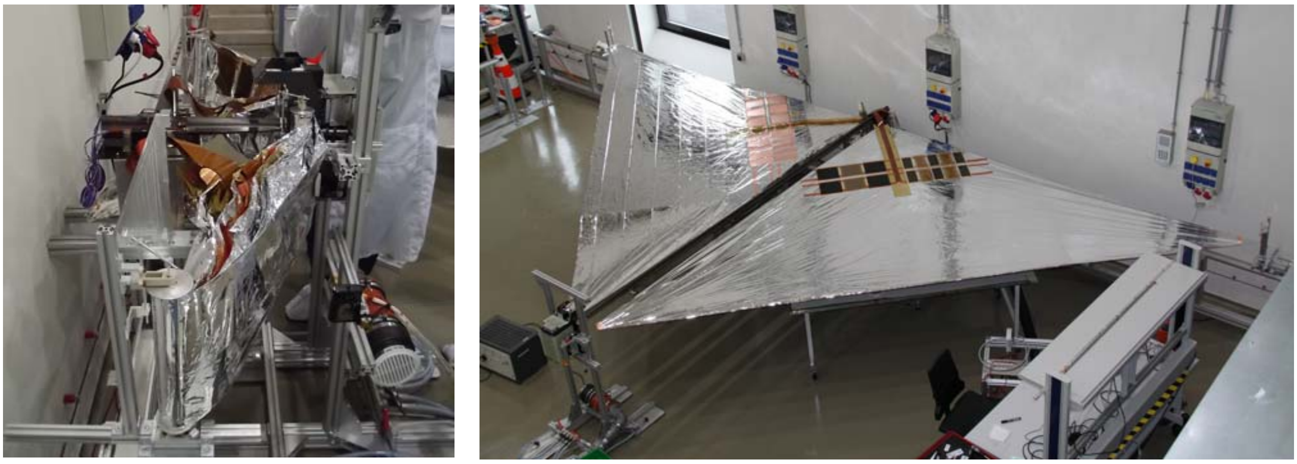


Fig. 21. Thermal Vacuum Test Secquence

Full Scale Deployment Test

The full scale deployement test is the last test for the qualification testing. Figure 22(a) shows the EQM BSDU with stowed sails mounted on the deployment test rig. Figure 22(b) shows the EQM BSDU in deployed configuration as well as the deployed sail segments with applied thinfilm photovoltaics or representative dummies. During this test a successful deployment shall be demonstrated. Futhermore, sail deployment loads will be measured with force gauges on the linear drives giving realistic numbers for boom loads during deployment for future sizing activities.



(a) stowed configuration (b) deployed configuration with applied photovoltaic

Fig. 22. EQM deployment test setup

During the test the BSDU will be commanded from the CSCU demonstrating the capability of controlling the deployment sequence by means of the common onboard computer of Gossamer-1.

4. CONCLUSION AND OUTLOOK

A deployment strategy was developed for a mission that aims to demonstrate a controlled and autonomous deployment in LEO. For this deployment strategy, a bus system as well as the required deployment mechanisms and electronics were developed, and engineering models of the hardware were built.

Deployment on system level was successfully demonstrated to be robust, controllable, and at no time at risk of entangling. The latter is guaranteed by the folding concept, which ensures that at each stage of deployment, only a minimum amount of the sail is released. The boom, BSI and BSDU proved to be suitable to drive the combined deployment of booms and sails. No negative interference between boom deployment and sail deployment was observed. The functionality of all involved mechanisms was demonstrated. The functionality of the electronics was demonstrated, i.e.

wireless control, deployment logic implemented, data acquisition, image acquisition by the on-board camera and a ground segment representative control via the electronics ground support equipment. A more detailed overview about the Gossamer-1 mission, hardware and verification is under review [19].
The deployment technology is on TRL four approaching level five, with an EQM for environmental testing currently being tested. The EQM of the deployment unit has already been successfully subjected to vibration testing and venting testing. Thermal vacuum is currently being cunducted. The test sequence will finally be concluded by a laboratory deployment testing.
The development of the solar sail specific technology will be stopped after the qualification process on a TRL five. The further development of deployment technologies will focus on solar arrays possibly based on thin-film photovoltaics. A DLR internal research programme GoSolAr (Gossamer Solar Array) is initiated to develop a 5 m x 5 m deployment demonstrator with experimental thinfilm photovoltaic. It is scheduled for an in-orbit demonstration on the second mission of the small satellite platform of DLR called S2TEP. The mission is considered to be launched in 2022 where for demonstration purposes the solar array shall provide power to the satellite bus as an experiment.
Future goal is the development of arrays with a power output of up to 50 kW (20 m x 20 m) for missions using electric propulsion.

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