Design of the Gossamer-1 Deployment Demonstrator

By Tom SPROEWITZ[1)], Patric SEEFELDTI[1)], Jan-Thimo GRUNDMANN[1)], Peter SPIETZ[1)], Norbert TOTH[1)]; Martin HILLEBRANDT[2)], Marco STRAUBEL[2)] and Martin ZANDER[2)]

[1)] *Institute of Space System of the German Aerospace Center, DLR, Bremen, Germany*
[2)] *Institute of Composite Structures and Adaptive Systems of the German Aerospace Center, DLR, Braunschweig, Germany*

Gossamer structures for solar sails, require a technology that allows a controlled and thereby reliable deployment. This is important to stop and restart the deployment in case of failures during deployment and to prevent an entanglement of the sail with other elements based on suitable sail stowing techniques. Before employing such a technology for a dedicated science mission, it is necessary, to demonstrate its reliability with a Technology Readiness Level (TRL) of six or higher.
The aim of the work presented is to provide an overview of the mission and of a system for controlled deployment. The development was conducted within the Gossamer-1 project of the German Aerospace Center (DLR).
For a system based on coilable booms and coated polyimide foils the design of the deployment mechanisms and electronics required is shown. The design is based on a crossed boom configuration with four triangular sail segments. According to a stepwise development of scalable gossamer systems, the design is implemented for a five by five meter sail. The satellite has an estimated mass of about 30 kg with a compact launch configuration with a maximum width of 790 mm and a height of 500 mm. Design drivers are explained and a mission design in presented.
By combining different functional principles respectively mechanisms a simultaneous deployment of the booms and the sail segments is achieved. The main innovation is to deploy the sail segments with deployment units that move away from the central satellite bus. This ensures that only a minimum amount of the sail is deployed that can be spanned between the deploying booms. By this the system is always in a mechanical stable state. The deployment can be performed in a slow and controlled manner and it can even be stopped and resumed if necessary without any risk of entanglement of the sail.
An innovative stowing and deployment strategy for a controlled deployment was implemented. It offers a possible solution for the deployment of solar sails and might also be adapted for other deployable structures such as photovoltaic arrays based on flexible thin-film photovoltaics.

Key Words: deployment systems, deployable structures, deployable membranes, solar sailing, verification testing, mechanisms

1. Introduction

In the last years, the DLR has pursued the development of a scalable deployment technology for gossamer spacecraft structures, suitable for autonomous and controlled deployment. A summary of those developments is given in this paper. While a focus was on solar sails and thin-film photovoltaics, the aim of the development is to provide a scalable technology for deployable membrane structures for various space applications. The development was made within DLR's Gossamer-1 project. It was initiated with the goal of developing the required deployment technology and its demonstration in LEO by means of a scaled demonstrator. An artist's rendering of this demonstrator is provided in Figure 1.

The development of solar sail technology in Europe and specifically at the 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 several 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 booms, as well as state of the art aluminum coated polyimide foils.

With respect to deployment and evolved mechanisms, it was recognized that previous strategies had disadvantages related to controlled and automatized 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, those earlier projects were not able to realize such a mission. Consequently, a step-wise development focusing on the deployment 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.

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, and each having 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]).

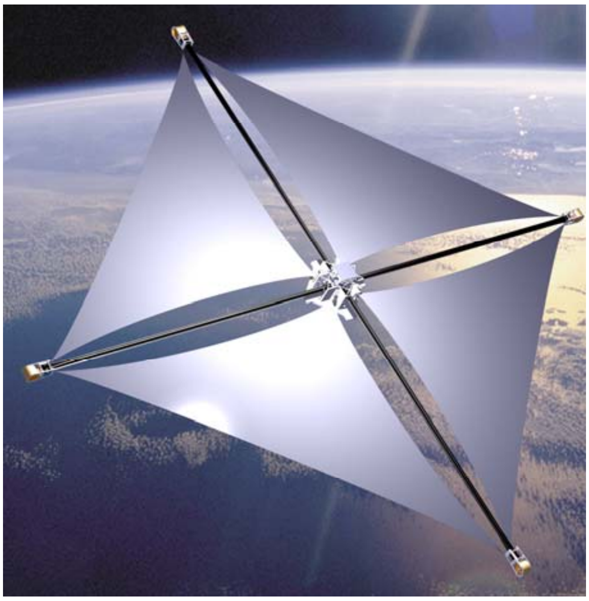
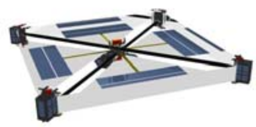


Fig. 1. Gossamer-1 demonstrator, artist's rendering

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.

(a) Launch Configuration



(b) During deployment

(c) Deployed

(d) Deployed with jettisoned mechanisms

Fig. 2. Gossamer-1 deployment sequence

It was planned to launch the Gossamer-1 satellite as secondary payload in the framework of 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. What was achieved was to design a technology demonstration mission and invent 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 sections.

2. Mission design

This section provides an overview of the most important requirements and the system compliance for a deployment demonstration mission (see Subsections 2.1 to 2.5). The resulting mission phases are described in Subsection 2.6.

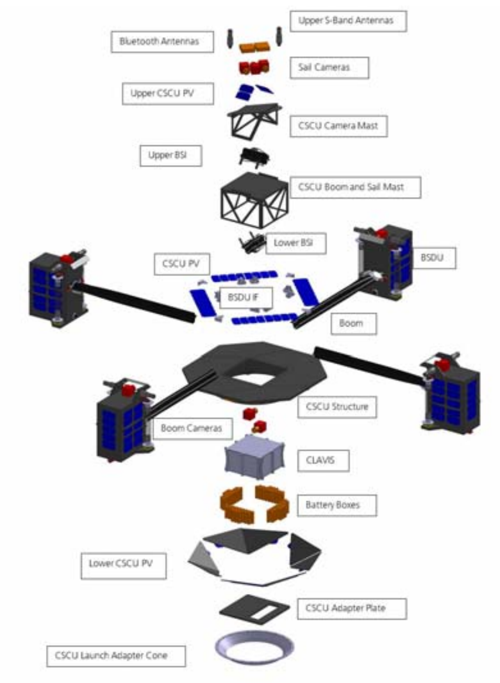


Fig. 3. Gossamer-1 exploded view

2.1. Orbit

As a deployment demonstrator, Gossamer-1 will not function as a solar sail. Consequently, it is not required to launch into altitudes where solar pressure is the dominant force. Therefore, the technology demonstration shall take place in a low Earth orbit with an initial perigee of no less than 350km driven by increased atmospheric drag at lower altitudes and the risk of mechanical destruction of the sail and boom structure by the drag forces. The apogee shall be no more than 800km due to increased radiation at higher altitudes.

The orbit shall have an inclination greater than 50° in order to use the ground station at Weilheim (Lat. 48°N) or Neustrelitz (Lat. 53 N) operated by DLR's German Space Operation Center. The QB50 mission launch (see Subsection 2.2) is compliant with those orbit specifications. Power, thermal and communication subsystems design is related to these orbits.

The orbit shall be compliant with the space debris mitigation requirements according to ISO24113 (2011). It is ensured that Gossamer-1 will reenter by natural orbit decay within 25 years even if the sail is not deployed. Gossamer-1 is mainly a demonstrator for solar sail technology, where the ratio of total mass to sail area is the driving factor for the performance of a solar sailcraft. Therefore, the deployment mechanisms shall be jettisoned. It is considered to be a mission critical element. It is done in a sufficiently low orbit, so that the orbit lifetime of the jettisoned mechanisms is on the order of weeks.

2.2. Launcher

A virtual launch vehicle was defined with a launch load envelope that results from a launch vehicle survey based on the planned launch of Gossamer-1 within the framework of the EC FP7 Project QB50 [7]. The survey considers the launchers Cyclone-4, Dnepr, Shtil(-1), Shtil-2R, Shtil-2.1, VEGA, Falcon-9, PSLV (including PSLV-CA, PSLV-XL), Eurockot Rokot-KM, Ariane 5ASAP (micro and mini) and Soyuz ASAP-S (micro and mini).

2.3. Ground segment

DLR's German Space Operations Center GSOC had to be used as the ground segment. For this reason the CCSDS standards were required and implemented. For Gossamer-1 mission objectives, S-band up- and downlink is sufficient, which is provided by GSOC ground station Weilheim.

2.4. Controlled deployment

The deployment process of Gossamer-1 shall be performed in a controlled manner to enable Failure Detection, Isolation and Recovery. It requires the possibility of obtaining system status information as well as possibilities for reacting to certain system states. Therefore, the deployment strategy ensures that the system is always in a mechanically stable configuration and the progress of the deployment is monitored.

The deployment of the Gossamer-1 demonstrator shall be performed autonomously by the spacecraft after being initialized by a ground command because the deployment process is conducted on a time scale of several minutes while ground control is limited. The deployment logic is correspondingly implemented in the software.

2.5. Visual documentation

The deployment process shall be documented by means of video sequences and/or images. This enables the evaluation and documentation of the functionality of Gossamer-1 and provides key data as a basis for future missions. The documentation strategy has to be optimized regarding data volume and accessibility of visual data for ground control in view of the S-band communications, possible short mission lifetime at low altitudes and FDIR strategies.

A camera system (see Subsection 3.4.2.) was implemented, taking pictures according to predefined patterns based on the deployment progress and not a time-based video capture with certain frames per second.

2.6. Mission phases

The duration of the considered technology demonstration mission is approx. 8 to 10 weeks in order to downlink the data generated during the deployment and to observe the system in space environment for some time. The deployment itself will only take about 10 minutes.

Figure 2 shows the deployment sequence of the Gossamer- 1 mission. Starting with the compact launch configuration shown in Figure 2(a), the deployment of the sail (Figure 2(b)) is generally finished with the configuration shown in Figure 2(c). At this point the sails are already separated from the sail spools and mounted to a fixation ring that is locked on the boom. An optional jettisoning of the deployment units would be possible (see above). However, it is understood that this option is only applicable in sufficiently low orbits. Figure 2(d) shows the sail craft after jettisoning. Encompassing and incorporating this purely deployment-related process, the mission is subdivided into 9 phases which take mission operation considerations into account.

2.6.1 Phase 1: launch and separation

During launch and separation the spacecraft is in the stowed configuration as shown in Figure 2(a). At separation, the spacecraft is activated by a launcher separation switch.

2.6.2. Phase 2: initial boot

In the initial boot process, the spacecraft is still in the stowed configuration. The on-board computer and the S-Band communication system are booted stepwise to allow close spacecraft control and FDIR in case of non-nominal behavior.

The first acquisition by the ground segment takes place in this configuration of the spacecraft. IT has enough autonomy and power to survive without ground contact for a sufficient time even if problems occur in the first acquisition.

The camera system on the central unit is booted and test images are taken. Status information and test images are downlinked. This phase shall last about two ground contacts.

2.6.3. Phase 3: BSDU power on and boot

The deployment units are switched on and booted one by one. The on-board wireless communication system is initialized and connections between the central unit and all deployment units will be tested.

After that, all five power systems (one on the central unit and one in each of the four deployment units) and their charging networks are configured to provide an optimum initial state of charge for each unit's battery.

The cameras on the deployment units are booted, test images are acquired and sensors are read out. All of these data are subsequently downlinked to ground.

The length of this phase is driven by the ground contact schedule. Two to three ground contacts are envisaged.

2.6.4. Phase 4: deployment

The deployment phase is started via a time tagged command to ensure that deployment starts in sunlight for good illumination and just prior to the next downlink such that nominal deployment will be done a few minutes before the actual ground contact. The deployment starts just prior to the next downlink in order to ensure that the system status is quickly known in the case of non-nominal behavior.

First, the deployment units are unlocked and the units move outward, deploying the booms and the sails at the same time (see Figure 2(b)).

Throughout the whole phase, images are taken by all 9 cameras. Likewise, data about position and moving speed of deployment units, deflection of booms as well as related housekeeping data is acquired for control of the deployment process. In case of non-nominal behavior, the system autonomously stops the deployment (emergency stop) and transits into a safe mode. Different cases for emergency stops are defined. In the case of such an emergency stop, all sensor data is read out and all cameras will take high resolution images. Such emergency stop data packages and corresponding historical data are subsequently downlinked with first priority at the next ground contact.

In nominal case, the deployment units will stop at the nominal deployment's end position and one part of the deployment unit, the boom-sail interface, will lock into the boom.

2.6.5. Phase 5: deployment units separation

As the next step the deployment units separate from the boom-sail interfaces and move a few centimeters away from the fixation point of the boom-sail interface while still remaining on the outer end of the booms. Before and after this separation, all cameras take high resolution images. After successful separation, image data, housekeeping data and science sensor data are transferred to the central unit and stored for downlink. This separation phase does not include a ground contact. Its duration is on the order of a few minutes.

2.6.6. Phase 6: deployment and separation data downlink

Image data amount to roughly 300 Mbytes for nominal deployment without housekeeping data and coding overhead. Between downlinks, the system enters a standby mode in which it autonomously performs ground contacts and science measurements (photovoltaics experiment, deflection measurements on booms) according to a predefined schedule.

Depending on the necessary number of ground contacts (approx. 10) this phase will last a few days.

2.6.7. Phase 7: intermediate monitoring phase

During this phase the system is mostly in standby mode. The system autonomously wakes up to take science measurements on the photovoltaics only according to a predefined schedule (e.g. transition from umbra to sunlight), as well as deflection measurements of the booms, acceleration measurements of the deployment units and magnetic field measurements for attitude determination.

Drivers for the length of this phase are the deflection and eigenfrequency measurements under different thermal and drag conditions. The duration is on the order of days.

2.6.8. Phase 8: BSDU jettisoning experiment

The jettison is a central part of the solar sail use case in order to minimize the mass of the sailcraft and maximize the characteristic acceleration, reachable with a solar sailcraft. After jettisoning all deployment units the spacecraft is in sailcraft configuration as shown in Figure 2(d).

The system reaction upon jettisoning will be observed by the cameras and strain gauges. The deployment units shall be jettisoned one by one in order to reduce the risk of collision. All cameras will take images in high resolution to provide information on visible boom deflections.

The jettisoned deployment unit will also take images and record data. Jettisoning is expected to last a few minutes. After reaching a distance of a few meters, the first phase of jettisoning is ended and imaging stopped. The second phase concentrates on catching images of the spacecraft with the camera of the receding deployment units to obtain an overall view of the spacecraft. The experiment is considered finished when the units are out of range of wireless communication.

The length of this deployment unit drift and observation phase is expected to be on the order of hours.

2.6.9. Phase 9: final monitoring phase

This phase is similar to Phase 7 without deployment units. The photovoltaics experiment is still fully functional and further information, e.g. about the degradation of the cells can be collected. During this phase the system is mostly in sleep standby mode. The system autonomously wakes up to take science measurements according to a predefined schedule.

3. Boom and Sail Technology

In the following paragraphs, the subcomponents and mechanisms will be described in more detail.

3.1. Booms

Gossamer-1 makes use of light-weight coilable, double omega 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).

(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. Gossamer Coilable thin shell CFRP booms and interfaces

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.

3.2. Sails

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 [8]. 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. Five single sheets are prepared. By bonding the sheet 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 as used for flexible PCBs. The connection between sails, booms and CSCU are made of 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 [9].

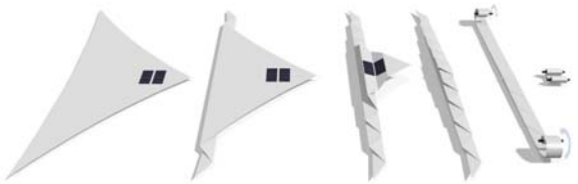


Fig. 5. Gossamer-1 sail stowing strategy for one of the four segments

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 by transfer adhesive. The modules are electrically contacted to a flexible PCB harness in the middle of the triangle. Currently the modules are experimental prototypes that are subject of ongoing studies.

3.3. Boom and Sail Deployment Mechanisms

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 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.

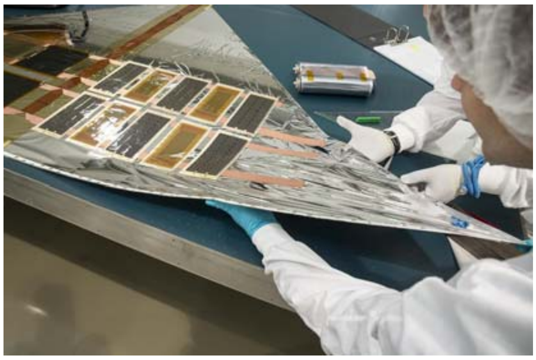
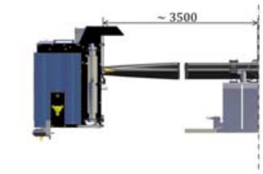


Fig. 6. Thin-film photovoltaic integrated on the sail foil

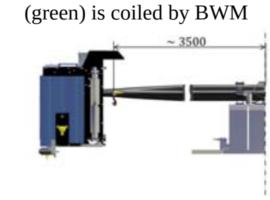
The uncoiling of the belt is driven by the belt winding mechanism (BWM) using an electric motor. To prevent uncontrolled deployment of the booms and sails the boom hub and the sail spools have brake mechanisms as described in the following dedicated paragraphs.

(a) Launch Configuration

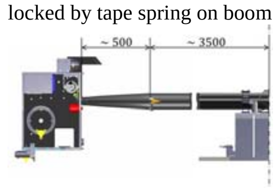
(b) BSDU is released and deployment started; the belt (green) is coiled by BWM



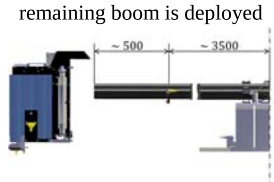
(c) Sails fully deployed; BSFR is locked by tape spring on boom



(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 representation, one BSDU without sail segments is shown

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).

3.3.1 Belt Winding Mechanism

The BMW 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 and an engaging copper beryllium spring plate.

The motor for the winding mechanism has to overcome torques induced by the boom hub, the boom guidance and the sail spool. 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 1.3x10-2 m/s for the slower mode and 6.3x10-2 m/s for the faster. It is desirable to use the slowest deployment speed possible in order to reduce inertial loads during deployment.

3.3.2 Boom Hub

The boom hub is a spool on which boom and belt are coiled. 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 releases the gear rotation in orbit.

In order to counteract the self-deployment of the boom due to stored elastic energy, the boom hub includes the aforementioned brake mechanism. Through the deformation of those leaf springs an oscillating torque with a maximum of about 0.25 Nm is generated.

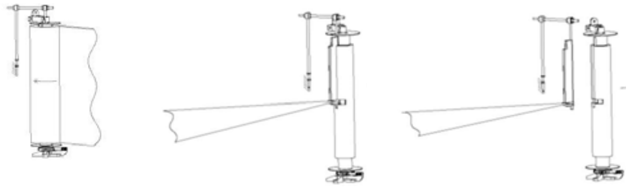
3.3.3 Boom Sail Fixation Ring

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 E250 STD from TiNi Aerospace Inc. It opens the mounting between BSFR and the BSDU.

3.3.4 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 8(a)). After the sail segment is uncoiled, the truss-like structure directly mounts the sail through the sail interface to the BSFR (Figure 8(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 8(c)). The patent of Seefeldt and Spietz [13] can be reviewed for details of the mechanism function.



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

Fig. 8. Sail separation sequence

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.

3.3.5 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 9.

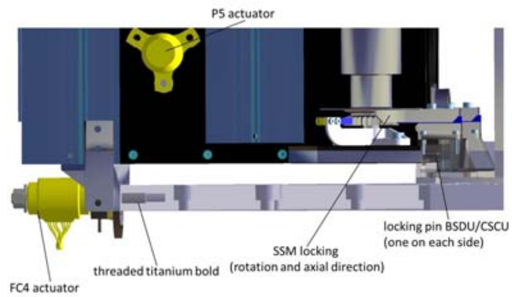


Fig. 9. BSDU Launch Locks

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. A cone shape for pin and holes was chosen in order to avoid clamping of the locked pin. 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 9 on the right and Section 3.3.4.

3.4. Deployment Monitoring

Systems for boom length measurement, boom loading measurement and a camera system were implemented.

3.4.1 BSDU Position Determination

In order to determine the position of the BSDUs during deployment two strips with reflective markers are laminated onto the boom flanges (see Figure 10). Using an optoelectronic sensor, it is possible to determine position based on counts of changes in reflectivity. Implementing periodically occurring calibration markers and a slight phase shift in the pattern provides higher robustness of position determination.

3.4.2 Camera System for Visual Documentation

The camera system consists of 9 cameras. One camera 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 use telemetric field optics and cover one boom and its deployment unit with a depth of field ranging from roughly the initial unlocking up to the final position.

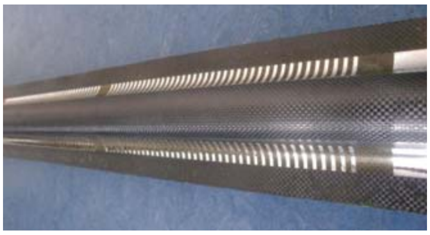


Fig. 10. Reflective marker on the boom

Image data volume acquired by the camera system is reduced by taking sequences of images rather than videos. The image data volume is decoupled from deployment speed by taking one image per 2.5 cm of deployment distance, as measured along the booms. Image data volume is further limited by taking sequences of images consisting of patterns of a number of low resolution images always followed by one high resolution image.

For the Gossamer-1 camera system a VRmagic VRmDC-8 Pro with a resolution of 2056 x 1544 pixels with Edmund Optics NT68-672 lenses for wide field and Pentax H1214-M lenses for telemetric application was selected.

3.4.3 Strain Gauges

During deployment, the 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.

4. Conclusion

A deployment strategy for a mission that aims at the demonstration of a controlled and autonomous deployment in LEO was developed within the DLR Gossamer-1 project. 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 and tested.

Based on mission and programmatic requirements a mission was designed enabling an in-orbit demonstration of a scaled ultra-lightweight deployable membrane with its primary use case for solar sailing. A secondary use case as photovoltaic array was also implemented in the mission design.

The technical design is presented with a focus on the design of the deployment unit, booms and membranes. Deployment on system level was successfully demonstrated to be robust, controllable and without risk of entangling. All mechanisms proved to be suitable to drive the combined deployment of booms and sails. 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. The deployment test set-up can be seen in Figure 11.

Fig. 10 EQM fully deployed during deployment test preparation

References

1) Leipold, M., et al., *ODISSEE - A proposal for demonstration of a solar sail in earth orbit*, Acta Astronautica, Vol. 45/4, 557-566, 1999.
2) Agnolon D., *Study overview of a solar sail demonstrator: GEOSAIL*, DLR/ESA, 2008.
3) Leipold, M, et al., *Solar sail technology development and demonstration*, Acta Astronautica Vol. 52/2, 317-326, 2003.
4) Leipold, M., Widani C., Groepper P. and others, *The European Solar Sail Deployment Demonstrator Mission*, Proceedings of the International Astronautical Congress, 2006.
5) Tsuda Y., et al., *Achievement of IKAROS - Japanese deep space solar sail demonstration mission*, Acta Astronautica, Vol. 82/2, 183-188, 2013.
6) Johnson, L., Whorton, M., Heaton, A., Pinson, R., Laue, G. and Adams, C., *NanoSail-D: A solar sail demonstration mission*, Acta Astronautica Vol. 68/5, 571-575, 2011.
7) Thoemel, J., Singarayar, F., Scholz, T. and others, *Status of the QB50 CubeSat Constellation Mission*, Proceedings of the 65th International Astronautical Congress, 2014.
8) Seefeldt, P., Spietz, P. and Sproewitz, T., *The Preliminary Design of the GOSSAMER-1 Solar Sail Membrane and Manufacturing Strategies*, Advances in Solar Sailing, 133-151, 2014.
9) Seefeldt, P., Steindorf, L. and Sproewitz, T., *Solar Sail Membrane Testing and Design Considerations*, Proceedings of the European Conference on Spacecraft Structures, Materials and Environmental Testing, 2014.
10) Straubel, M., Seefeldt, P., Spietz, P. and Hühne C., *The Design and Test of the GOSSAMER-1 Boom Deployment Mechanisms Engineering Model*, Proceedings of the 2nd AIAA Spacecraft Structures Conference, 2015.
11) Ho, T., Baturkin, V., Grimm, C., Grundmann, J. T., Hobbie, C., Ksenik, E., Lange , C., Sasaki, K., Schlotterer, M., Talapina, M., and others, *MASCOT - The Mobile Asteroid Surface Scout Onboard the Hayabusa2 Mission*, Space Science Reviews, Vol. 1-36, 2016.
12) Zander, M. E., Sinapius M, and Hühne, C., Preliminary Experiments for an On-Orbit Detection system to Monitor Load and Deflection States of Thin Shell CFRP Booms for the Solar Sail Demonstrator Gossamer-1, Proceedings of the European Conference on Spacecraft Structures, Materials and Environmental Testing, 2014.
13) Seefeldt P. and Spietz, P., Raumfahrzeug-Membranentfaltungssystem und Verfahren zum Betrieb desselben, Pending Patent 2016.