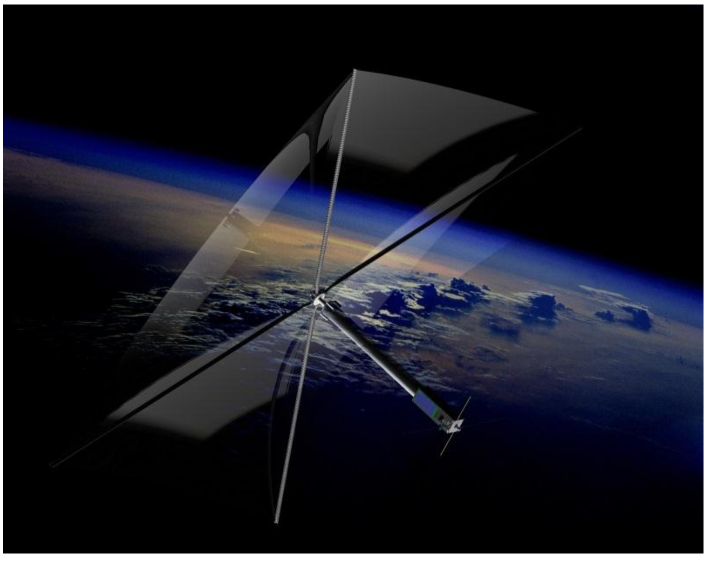
3.1 Publishable summary

DEPLOYTECH is a three part project whose primary focus is the increase in Technology Readiness Level (TRL) of promising deployable space technologies. The three technologies concerned are:

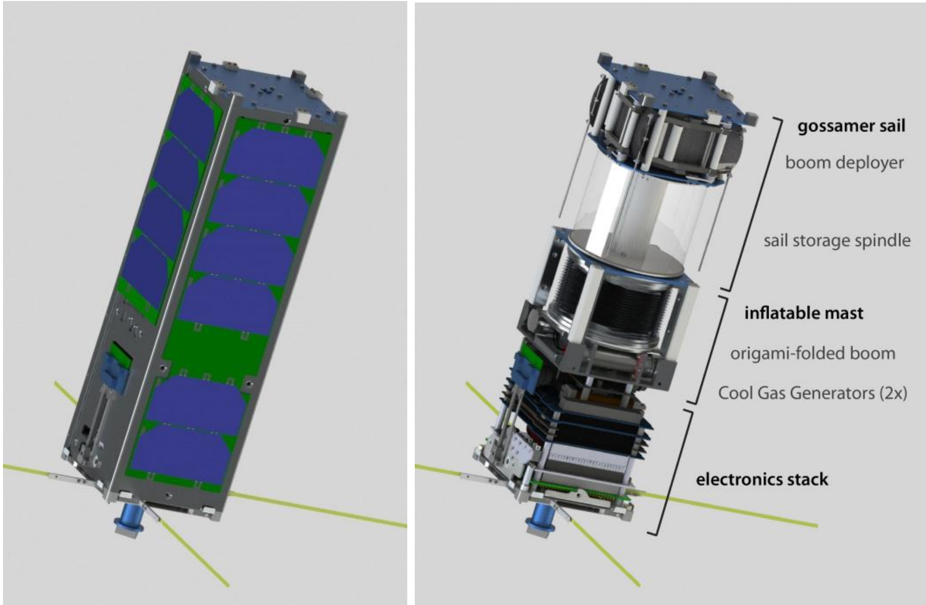
- Inflatable structural components for satellites in the micro-nano satellite categories;
- Bistable Reeled Composite (BRC) deployable booms (with special reference to solar array applications) for mid-large sized satellites;
- Closed-section lenticular carbon fibre deployable booms for solar sails.

3.1.1 InflateSail

InflateSail is a technology demonstration mission for a drag deorbiting system. Two gossamer structures are deployed from a 3U CubeSat: a 1m long inflatable-rigidisable mast, and a 10 m^2 drag sail supported by bi-stable CFRP deployable booms. The InflateSail satellite will be launched as part of the European QB50 mission in 2016.



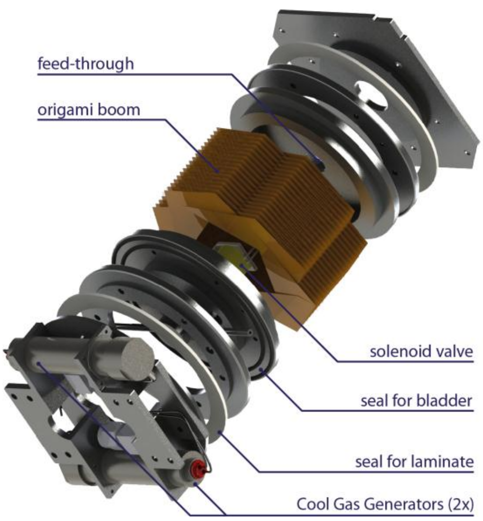
The objectives of the InflateSail mission are to demonstrate the potential of a sail-mast system as an end-of-life deorbiting solution for larger satellites. The deployable sail would increase a host satellite's aerodynamic drag, thus reducing its orbital decay time. The inflatable mast provides an offset between the centre-of-mass of the host satellite and the centre-of-pressure of the gossamer sail, which facilitates passive attitude stabilisation and thereby maximises the presented drag area. Additionally, InflateSail will demonstrate the use of an aluminium-polymer laminate inflatable cylinder as a lightweight deployable structural member, and use a Cool Gas Generator (CGG) for storage and release of the inflation gas.

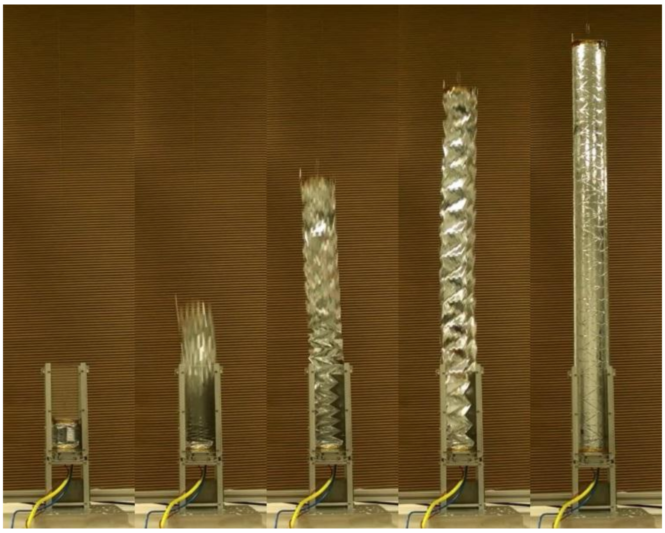


In the course of this project, the complete InflateSail satellite was designed, constructed, and tested. The primary engineering challenge was to design the large deployable structures to fit within the limited space available in a 3U CubeSat (10 x 10 x 34 cm) and reliably deploy to their full dimensions. The experimental payloads (the inflatable mast and deployable sail) were developed and their functionality verified through a qualification campaign.

Inflatable-Rigidisable Mast

In its deployed configuration the inflatable mast assumes a length of 1 m and diameter of 90 mm, and for launch it is folded down to a height of 63 mm using an origami pattern. The skin material consists of an aluminium-polymer laminate; after deployment the residual creases in the membrane are removed through plastic deformation of the aluminium-laminate material. This step ensures long-term structural performance of the inflatable boom, without the need to keep the boom pressurised.



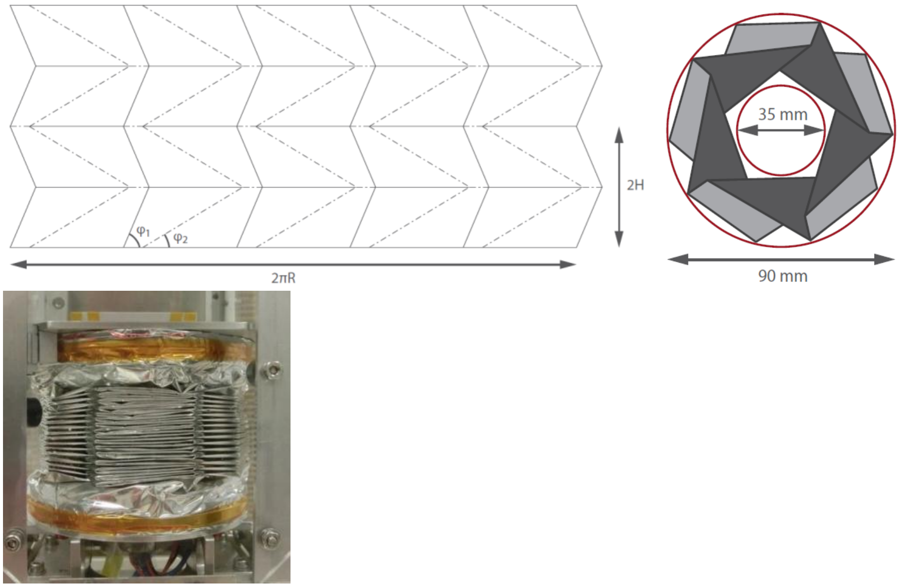


The Cool Gas Generator (CGG) inflation system was custom-developed for this mission by TNO and CGGTechnologies. Two CGGs are installed immediately below the folded cylinder. A single

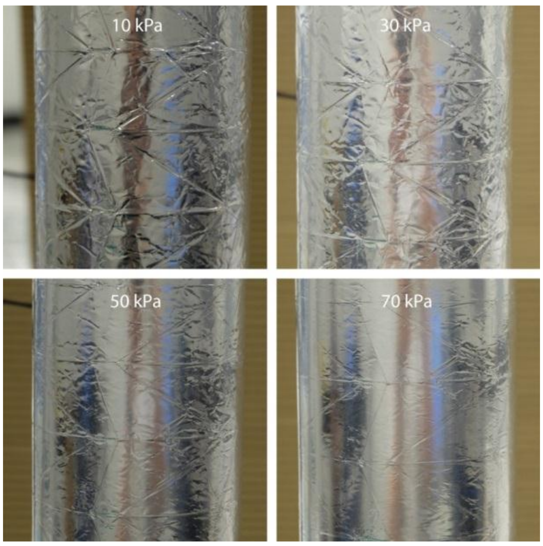
CGG is sufficient to perform the inflatable deployment and rigidisation, with the second included for redundancy.

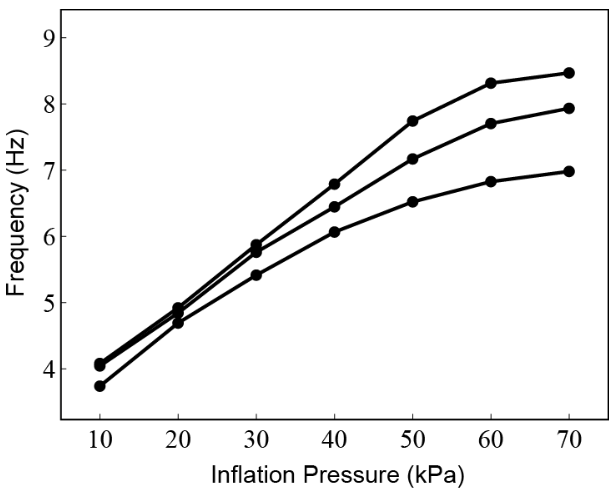
In the development of the inflatable mast, key results include:

- Development of the origami packaging technique, enabling the 1 m long boom to fold down to a height of less than 65 mm, while still being able to deploy rapidly. A key challenge was the limited dimensions of the inflatable mast, and a novel manufacturing technique was required.



- Demonstrating the efficacy of strain-rigidisation in ensuring long-term structural performance of the inflatable mast, by removing the residual creases in the Aluminium-laminate skin material. Characterising the stiffness and strength of the deployed boom was further complicated by difficulties in accurately measuring the material properties of the laminate material.

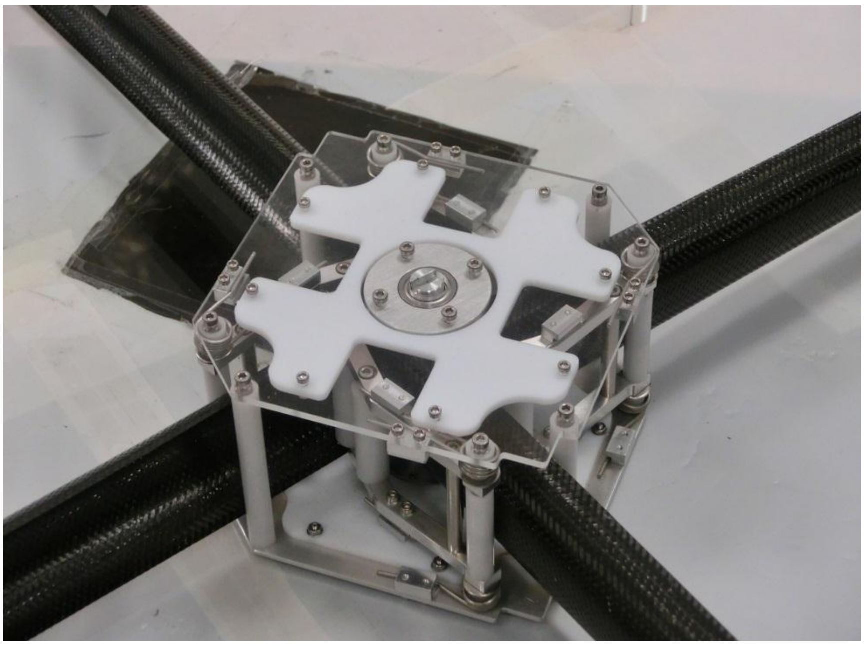




- Environmental testing of the deployable mast, including deployments in vacuum conditions using Cool Gas Generators. Under vacuum the gas release of the CGGs is very fast, requiring the inflatable mast to be able to deploy rapidly. Ascent vent tests demonstrated the ability of the inflatable to release any residual air inside the folded boom; this is required to avoid self-deployment of the boom during launch of the satellite.

Sail Deployment System

The sail deployment module consists of two components: the boom deployment system, which stores and deploys the four co-coiled CFRP booms, and the sail storage spindle, around which the four sail quadrants are wrapped. The system is an updated version of a design previously qualified at SSC, with as notable improvements a low-friction sail deployment spindle to reduce deployment loads on the booms, and a smaller boom coil to mitigate blossoming. The sail deployment system went through vibration testing and was successfully deployed at thermal extremes.



Gossamer Deorbiting System

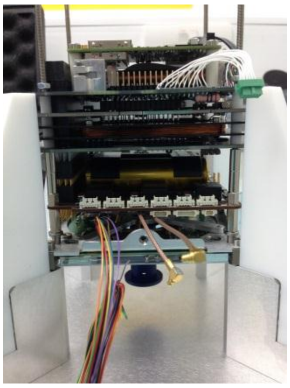
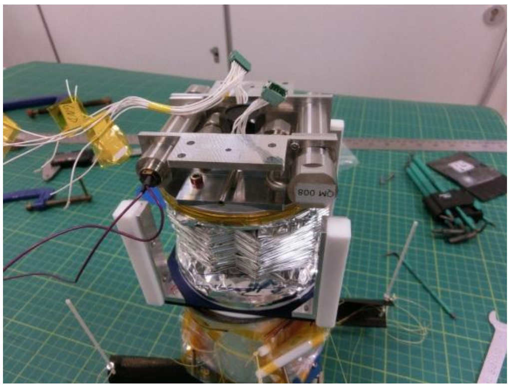
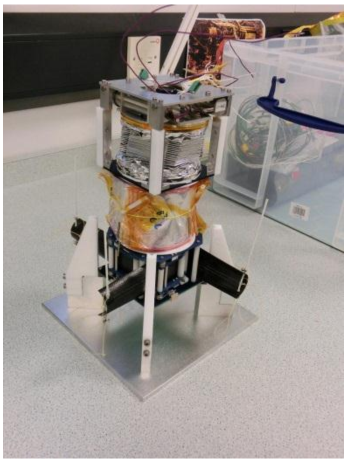
The outcome of the InflateSail development was a 3U CubeSat with full avionics stack (antennas, radios, power system, attitude determination and control system) and two large deployable structures as payloads.

An engineering model of the combined gossamer sail and inflatable mast is shown fully deployed:

Flight Model

A flight model of InflateSail has been constructed to fly on the QB50 mission. The final functional test of the sail system is shown below:

The satellite avionics stack, and the construction of the flight inflatable module are shown below:

3.1.2 Cool Gas Generators

In the first section, the start of Deploytech will be discussed, including the set-up of the requirements. In the second section, the design process of the Small Modular CGG will be discussed and in the third section, the production and testing of the SMCGG's is described. In the final section, the design, test and verification documentation is given.

Proposal phase

In the proposal for Deploytech, the CGG was identified as an interesting option to inflate small inflatable structures. Before Deploytech two options were available:

1) A pressurized gas system with a tank, valves and a regulator. Used in most inflatable structures that have flown in space. Advantage: proven and qualified technology, gas at ambient temperature. Disadvantage: complex, may leak, high pressure, expensive, not easy to miniaturize, limited life time

2) Hot gas generator as used in the American Mars landers. Advantage: proven technology, simple and rugged, long life time. Disadvantage: only for short duration inflation, hot gas cause several thermal problems, not available in Europe (although basic gas generator technologies do exist in Europe)

Deploytech wanted to explore a new European technology, the Cool Gas Generator, developed by TNO in the Netherlands. It is similar to a hot gas generator, except that it produces a pure gas at ambient temperature instead of a mixture of hot gasses. The CGG allows for a simple and rugged system with a long life time, and gas at ambient temperature.

However the CGG had never been demonstrated with an inflatable system and in fact no suitable CGG existed. Therefore a new CGG design was conceived, the Small Modular CGG, short SMCGG. The idea was to design a small CGG that could be easily modified to provide different amounts of inflation gas for different applications.

The work would start at the start of Deploytech and was planned to be finished in two years with the delivery of QM CGG's for testing at the Surrey Space Centre. The development followed a traditional approach with first an Engineering Model to be built and tested and then to progress to a Qualification Model. Spare Qualification Models might be used by SSC for flight units.

Introduction to CGG’s

Cool Gas Generators are solid propellant motors with a solid propellant charge in which the gas is chemically stored. When started, a chemical reaction is started in which the gas is formed. The reaction is designed in such a way that the residuals (chemicals that or not part of the gas that is formed) of the decomposition stay in the generator as a slack material. The generator is designed in such a way that the output gas has ambient temperature when it leaves the generator. The gas composition can be an almost pure gas. This combination extends the applicability of cool gas generators far beyond that of conventional solid propellant gas generators. Up to this moment, CGG’s for nitrogen and Oxygen have been extensively tested and are being commercialized. Furthermore CO_2 and hydrogen generators are in development.

A 40 normal liter Cool gas Generator for terrestrial applications [APP]

The proposal for DeployTech was writing by the end of 2010. At that time, the commercialization of the CGG was starting up and CGG Technologies was being planned, but was not yet founded. Therefore it was decided that CGG Technologies would be brought into the project if DeployTech should be awarded by the EU. This happened at the end of 2011 and at that time CGG technology was a functioning company. The activities were split among CGG Technologies and TNO in the following way. CGGT: lead, system design and interfaces, documentation, casing design and manufacturing, pressure and leak testing. TNO: grain design and testing, igniter design and testing, CGG testing, classification testing

System Definition Phase of Deploytech

After the project start early 2012, the system definition phase started in which the InflateSail system was defined. The start-up of this phase was slow as it took a long time to get the definition of InflateSail to a level that meaningful design work could be started on the CGG. In the second half of 2012 the first designs appeared and the first specifications were drawn up. By the end of 2012 the design work had begun.

SMCGG design

The system design activities for InflateSail continued in 2013 and the CGG design effort continued to feed the system design and analysis on InflateSail level with the best data on the CGG. In the summer of 2013, during a meeting at TNO, the design was frozen on its main requirements like the gas volume of 3 nl was finally selected. The requirements document was adapted to include the decisions taken in these meetings. The first major issue of the design description was completed soon after this meeting. I the second half of 2013, the design of the SMCGG was worked out in detail, especially the fluid and mechanical interfaces. In the production drawings for the grains were completed and they were already produced in third quarter of 2013 and put into storage.

In the first quarter of 2014 the design was worked out in construction drawings for the machining company. Several sessions were held with TNO and the machining company were held to optimize the design in both mass as well as production costs. In May 2014 the drawings went to the machining company and production started.

Early June the tests resumed with the Physical properties test of the DM and QM hardware. All hardware passed these tests.

The DM SMCGG (left) undergoing pressure tests with the pump to the right

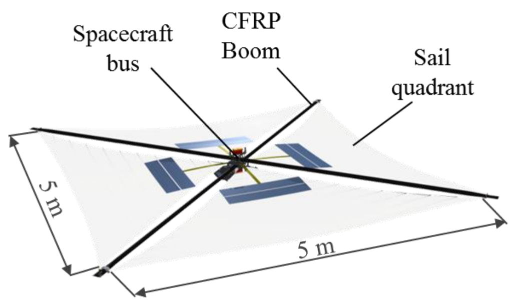
After these tests, the CGG were assembled with the already produced grains to form complete units. At TNO the firing test campaign started on the 9th of June 2014 and lasted for a week. First DM tests were conducted without grain and were used to confirm the breaker test results, later on different firing test were conducted. An important test was the classification test. The results of this test showed that the CGG could be transported as a non-hazardous item.

After the tests the first CGG's were shipped to the Surrey Space Centre for further testing with the other Deploytech hardware. These tests included three firings with Deploytech hardware in which the Inflatesail structure was inflated. When the first tests were completed at Surrey, the remaining CGG's were assembled and sent to Surrey in September 2014.

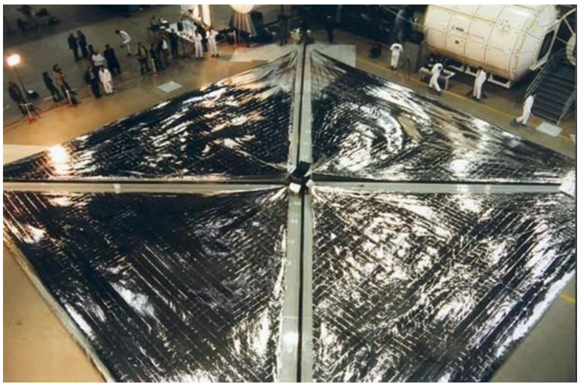
3.1.3 DLR Booms for GOSSAMER 2

As the second step in the DLR/ESA´s "Gossamer Roadmap" Gossamer-2 will be a 20 m x 20 m, 3-axis stabilized, squared solar sail deployment system featuring limited orbit and full attitude control. This is planned to be demonstrated in a 500 km altitude orbit. Furthermore deployment itself, monitored by several cameras and power generation using thin film photovoltaics will be demonstrated. It is obvious that such an ambitious system needs the suitable hardware components such as booms and deployment mechanisms.

Aiming for an ultra-light weight deployable technology that is scalable in size and complexity, system components are scaled up from the prior step in the "Gossamer Roadmap" Gossamer-1, a 5 m x 5 m in-orbit squared solar sail technology demonstrator. Like Gossamer-1, Gossamer-2 is utilizing the same basic design with two crossing CFRP booms mounted on the main satellite structure, which are deployed by four autonomously acting mechanisms, that hold the stowed sails as well as the flattened and coiled booms. The basic design is given in Figure 1, as the left image shows the Gossamer-1 solar sail and the right image the previous study leading to the “Gossamer Roadmap”, the ODISSEE 20 m x 20 m ground demonstrator of DLR and ESA. The typical deployment sequence of Gossamer-1 and Gossamer-2 is illustrated in Figure 2: Starting with a stowed spacecraft, four deployment units deploy the thin shell CFRP booms and sail quadrants simultaneously. Once the full size is achieved the deployment units jettison themselves off leaving a lighter sailcraft ready for function demonstration.



a) Gossamer-1 Solar Sail design



b) ODISSEE 20 m x 20 m ground demonstrator

Figure 1: Squared solar sail design at DLR

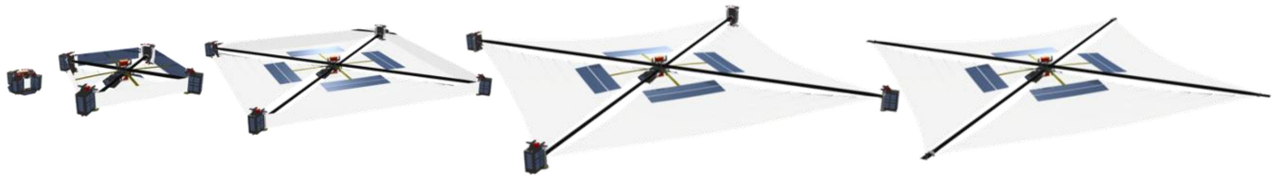


Figure 2: Typical deployment sequence of Gossamer-1 and Gossamer-2

Within DEPLOYTECH booms as well as the deployment mechanisms are scaled up and designed to work for the 20 m x 20 m in-orbit sail demonstrator Gossamer-2. Figure 3 illustrates the scaling from Gossamer-1 sail size to the Gossamer-2 sail size. Here the booms are not only scaled up in length, furthermore they are scaled up in cross section, while the cross sectional geometry is adjusted to larger geometric dimensions. Dealing with larger booms and larger sails, the deployment units as well are scaled and adapted to fit Gossamer-2, as part of the DEPLOYTECH project.

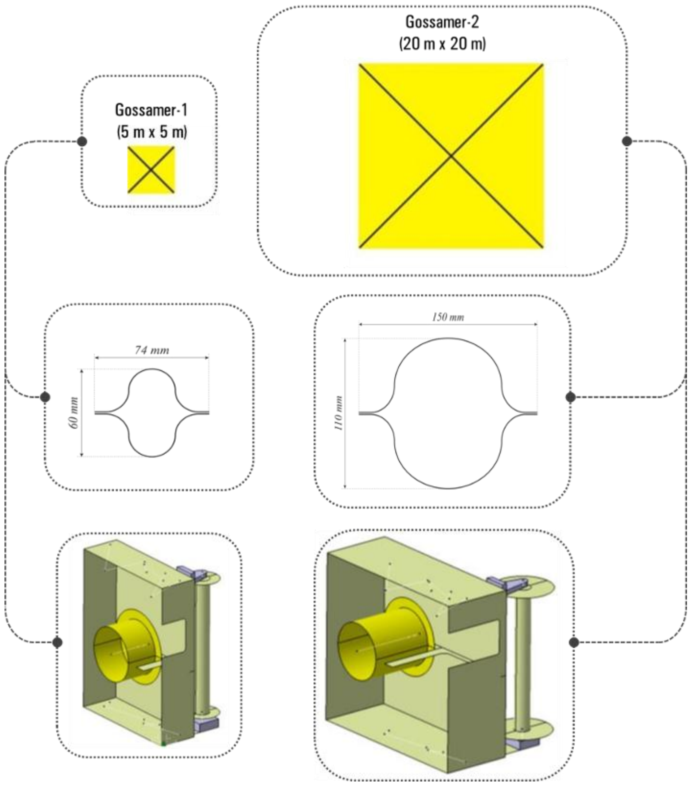


Figure 3: Scaling solar sail technology from Gossamer-1 size to Gossamer-2 size (sails, booms, deployment units)

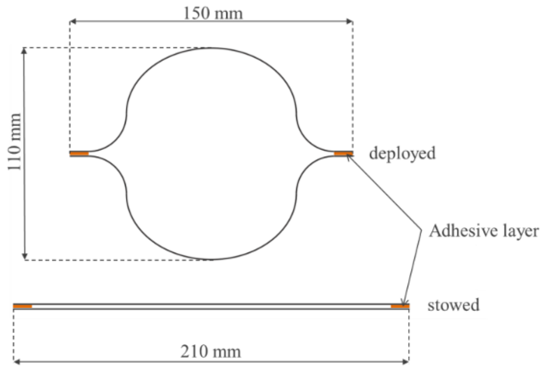
Boom Design and Manufacturing

The thin-shell CFRP booms used for Gossamer-2 and investigated within DEPLOYTECH are made of a 0.14 mm thin, 0/90 plain-weave prepreg (pre-impregnated CFRP material). The booms feature a double-Ω shaped cross section (sometimes referred to as lenticular). Each of the two crossing booms are joined from two 14 m long boom segments to a total length of about 28 m, thus using four 14 m boom segments. Gossamer-2 booms are scaled up from the Gossamer-1 booms as explained. In Figure 4 a size comparison of a Gossamer-2 boom and a Gossamer-1 boom manufactured at DLR is illustrating the size and material appearance.

Figure 4: Comparison of a Gossamer-2 boom (right) and a Gossamer-1 boom (left) built at DLR

To stow these large boom structures the boom are flattened in cross section and rolled up on a cylindrical hub that is part of the deployment unit. A partially flattened and rolled up boom in stowed configuration is depicted in Figure 5 a), while in Figure 5 b) the cross sectional dimensions in a fully deployed configuration and in stowed configuration is given. Although the booms possess intrinsic stresses when stowed, the booms alone do not deliver sufficient deployment force to deploy themselves and the sails. Thus, the deployment units are needed providing the deployment force and a controlled process of deployment.

a) Partially flattened and rolled up boom



b) Boom dimensions, deployed and stowed

Figure 5: Boom stowage and cross sectional change

The booms are manufactured from half-shells with a thickness of 0.14 mm, made of 0/90 plain weave CFRP prepreg cut to stripes. The CFRP raw material (prepreg) has an aerial weight of 94 g/m², resulting in the specific mass of the booms of about 60 to 70 g/m. After cutting the prepreg stripes roughly to size, they are formed into the 14 m long tools and cured under vacuum and high temperatures between 80 and 200 °C. Then each half shell is trimmed along the edges to the final size. The produced half shells (see Figure 6 a) are then bonded to another at their flanges using an adhesive, as shown in Figure 5 b). Followed by another curing cycle (tempering) to increase the adhesive´s strength, the finished boom can be unformed, as shown in Figure 6 b). For mechanical boom testing and deployment tests the produced 14 m boom was cut into shorter boom specimens (see Figure 7) in order to fit into the test stand and to be able to test different load regimes with undamaged booms.

a) Cured 14 m boom half shells in the mould-tool

b) Unforming a 14 m boom

Figure 6: Boom manufacturing at DLR

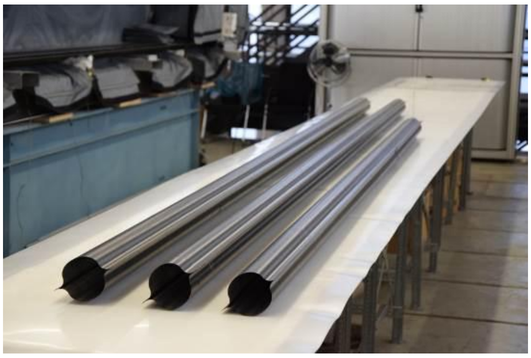


Figure 7: Boom specimens for mechanical and deployment testing

Deployment Unit Design

Concept

As the interfaces of potential launch vehicles for GOS-2 are unknown the BDU should be used universally. In this regard upper and lower interface sections can be designed and attached later to the BDU. These interface sections shall also be used for accommodating the sail spools. For realizing a boom deployment in two planes like GOS-1 the BDU is based on a flip-over design.

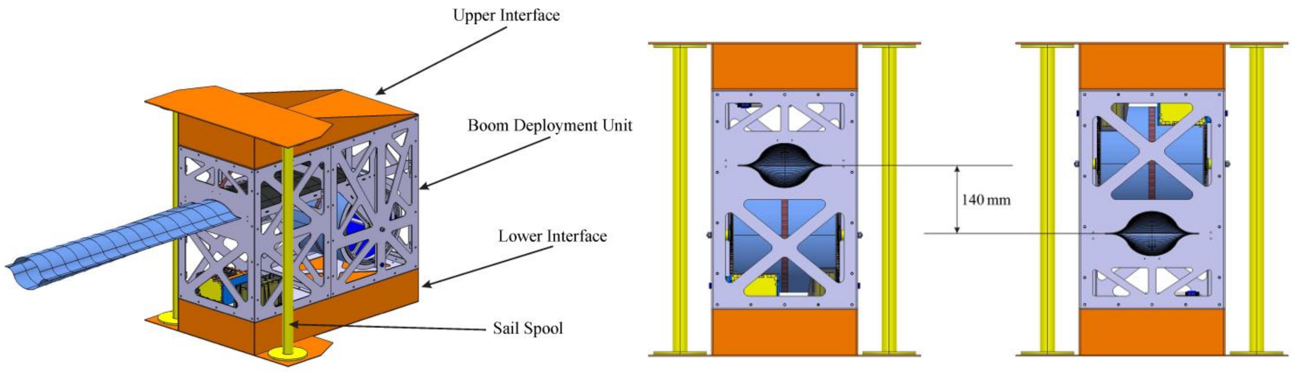


Figure 8: BDU design concept (left) and front view of the BDU in both configurations (right)

BDU Design and Functionality

In **Figure 9** the core components of the BDU design, which include the CFRP boom, the Belt Winding Mechanism, the Battery and Electronic Box, the Boom Guidance System as well as the Coiling Hub are shown. All structural components are machined out of aluminium. Only the boom guidance half shells are made out of CFRP.

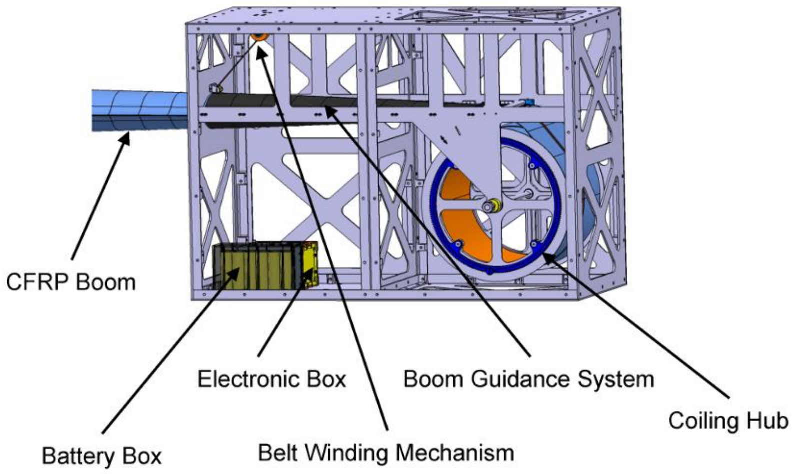


Figure 9: Overview of the BDU core components

The boom deployment is controlled by an electric gear motor, which is directly coupled to a winding mechanism for a steel belt. Beginning from the belt spool the steel belt is guided around a deflection pulley through the CFRP guidance half shells towards the boom spool. On one end it is attached to the belt spool and on the other end it is fixed to the boom spool. Furthermore the steel belt is co-coiled with the boom on the boom spool. The deployment of the boom is driven by the up reeling process of the steel belt by which the boom is pulled out of the coiled boom package.

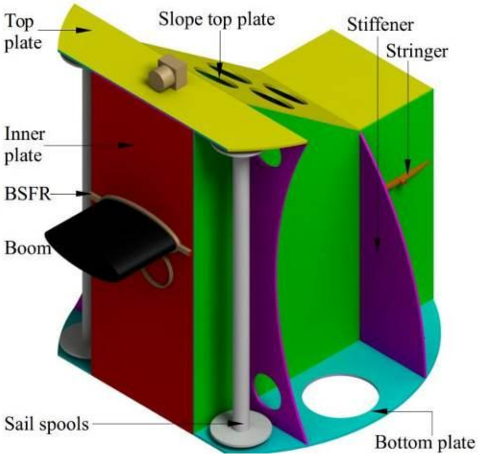
Scaling and BDU dimensions

In the up-scaling process of the BDU from GOS-1 to GOS-2 size the principles of the mechanisms could be taken over but almost all geometrical dimensions must be adapted. So the boom spool width has to be adjusted to the bigger GOS-2 boom. Also the diameter of the boom spool must be changed from 100 mm to 200 mm to ensure an adequate boom coiling for reducing local buckling.

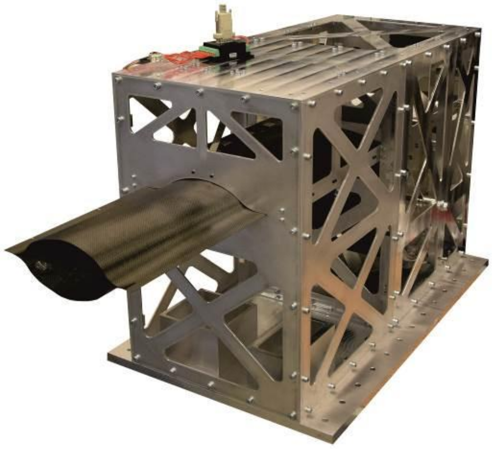
The outer dimensions of the BDU are driven by the boom spool width and diameter, the minimal necessary boom supporting length and the offset between the two deployment planes. Considering these parameters the outer dimensions follow to a length of 650 mm, a width of 300 mm and a height of 450 mm.

BDU Evolvement

A preliminary design study for a potential boom and sail deployment mechanism for GOS-2 size was performed by M. Richter during his diploma thesis. Within this study three different concepts are designed and evaluated. In the end the most suitable concept bases on a shell design, which shall entirely be made out of sandwich plates. As mentioned before the interfaces for possible space vehicles are unknown. That is why the concept for the deployment mechanism has changed toward a development of an universally useable BDU design. In **Figure 10** the shell design of the preliminary design study (left) and the current prototype of the boom deployment mechanism (right) are shown.



a) Shell design from a preliminary study for a boom and sail deployment unit for GOS-2



b) Current design of the boom deployment unit prototype

Figure 10: Evolvement of the BDU design concept