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THE FACULTY OF POWER AND AERONAUTICAL ENGINEERING
WARSAW UNIVERSITY OF TECHNOLOGY

PW•SAT2

PRELIMINARY DESIGN REVIEW

DEPLOYMENT TEAM

August 2015

Abstract

The following document is a part of Preliminary Design Review – a paper describing the Phase B of student satellite project called PW-Sat2. Several analyses where conducted to determine communication sessions duration and frequency, eclipse duration and maximum sun exposure for 7 possible destination orbits for PW-Sat2.

Revisions

Date	Changes	Responsible
2015-05-17	First Revision of this document	Ewelina Ryszawa
2015-05-29	Editorial changes	Dominik Roszkowski

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Abbreviated terms

AR – Acceptance Review (as defined in [RD.1])

CONF - Configuration Team

DT - Deployment Structure Team

DS -Deorbit Sail

EOL – End Of Life

ESA – European Space Agency

FEA - Finite Element Method

FRR – Flight Readiness Review (as defined in [RD.1])

PDR – Preliminary Design Review (as defined in [RD.1])

SADS - Solar Arrays Deployment System

SC – Spacecraft

SKA – Studenckie Koło Astronautyczne (Students' Space Association)

SRM - Sail Release Mechanism

SW – Software

TBC – To Be Confirmed

TBD – To Be Defined

WUT – Warsaw University of Technology

1 INTRODUCTION

1.1 PURPOSE AND SCOPE

This document describes the activities of the Deployment Structures team of PW-Sat2 satellite project during phase B. Main activity of phase B were:

- development work on deorbit sail
- construction of solar arrays deployment system
- design of mechanism for deorbit sail deployment
- construction of the sail assembling stand
- construction of the test stand for PW-Sat2 integration

1.2 DOCUMENT OUTLINE

The document is structured as follows:

- Chapter 1 contains an introduction to the document
- Chapter 2 provides the applicable and reference documents
- Chapter 3 provides the revision of phase A activities
- Chapter 4 provides the work done on the deorbit sail and subsidiary components
- Chapter 5 provides the description of the SADS
- Chapter 6 provides summary and planned activities for phase C

1.3 DOCUMENT CONTRIBUTIONS

This document and any results described were prepared solely by PW-Sat2 project team members. As of this revision, this document is planned to be delivered to external entities for review, particular entities are yet TBD.

2 REFERENCES

2.1 PROJECT DOCUMENTS

Table 2-1 List of applicable project documents

Ref.	Title	Code	Version	Date
[PD. 1]	PW-Sat2 – Preliminary Requirements Review – Mission Analysis	PW-Sat2_10_PRR_MA_EN	1.0.1 EN	2014-07-02
[PD. 2]	PW-Sat2 – Preliminary Design Review - Summary	PW-Sat2_00_PDR_Overview	1.0	2015-05-17

2.2 REFERENCE DOCUMENTS

Table 2-2 List of applicable reference documents

Ref.	Title	Version	Date
[RD. 1]	ECSS-M-ST10C – "Space project management."	Rev.1	2009.03.06
[RD. 2]	*http://space.skyrocket.de/doc_sdat/gomx-1.htm*		2015.05.09
[RD. 3]			

3 REVISION OF PREVIOUS WORK

During Phase A the following tasks were defined for the Mission Analysis Team:

3.1 PHASE A ACTIVITIES

As described in [PD.1] Phase A activities included:

- First design and models of deorbit sail
- First design of solar arrays deployment system
- Design of satellite main structure

Phase A document [PD.1] contents also a detailed description of deorbit sail operation and preliminary risk analysis. Therefore, these elements have not been repeated in this document.

3.2 REVISION

Table 3-1 Task revision from phase A

Description	Comment
Flat springs shape optimization	This task activities are presented in the chapter 4.1 of this document.
More precise sail model and its tests	This task activities are presented in the chapter 4.1 of this document.
New material of flat springs (beryllium bronze)	This task activities are presented in the chapter 4.1 of this document.
Different materials of sail surface (films, MLI)	This task is scheduled for phase C; more information in chapter 4.1
The ejectional cone spring – different parameters	This task activities are presented in the chapter 4.3 of this document.
Design of the sail container inside the satellite structure	This task activities are presented in the chapter 4.2 of this document.
Design of the system stiffening cone spring after deploying	This task activities are presented in the chapter 4.3 of this document.

Tests of optimal model in simulated microgravity conditions	This task activities are presented in the chapter 6.1 of this document.
Improvement of the opening-braking system and the system holding panels in their demanded position,	This task activities are presented in the chapter 5.1 of this document.
Integration of the hinges’ real models	This task activities are presented in the chapter 5 of this document.
Tests of the hinges’ models	This task activities are presented in the chapter 5 of this document.
Possible modifications of the elements and their further tests,	This task activities are presented in the chapter 5 of this document.
Careful choice of the hinges’ materials.	This task is scheduled for phase C
Main structure development	This task has been transferred to Configuration Team
CONF separation	Team separated in May 2014

4 DEORBIT SAIL

Deorbit sail is the main payload on-board PW-Sat2 satellite. In this project the primary objective is to test the designed system and verify its effectiveness. PW-Sat2 deorbit system will be a square sail of 2 m side. The material of the sail is stretched on four flat springs and wrapped around specially shaped roller. This construction will be deployed 20 cm above the satellite. On one side of the satellite a small camera will be mounted to observe the opening process of the sail so the team will be able to analyse it for future improvements and development. The lifetime of PW-Sat2 on orbit will be compared to the other satellites on similar orbits.

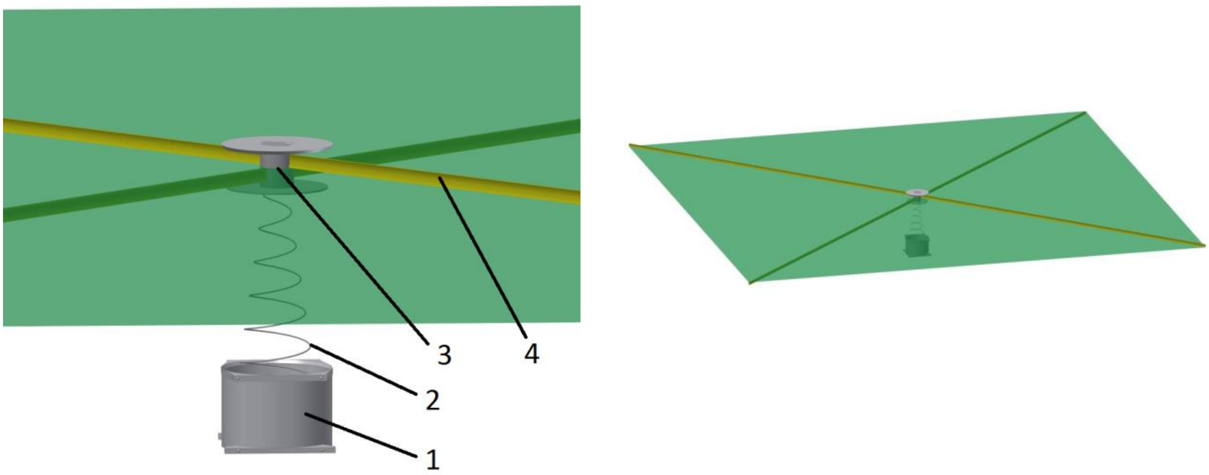

Figure 4-1 Design of the Deorbit Sail; Left: Sail deployment mechanism close-up, (1) – sail container, (2) – sail conical spring, (3) – sail reel, (4) – sail flat springs; Right: sail deployment mechanism overview

4.1 CONSTRUCTION OF THE SAIL

Sail is made of a reel and flat C-shaped springs wrapped around it. The material is a square with sides of 2m long. On its diagonals four "pockets" are attached. Sail arms are mounted inside them. Each arm consists of two flat springs that together form the shape of a L-beam. The pocket is glued to one of the springs (internal) while the other can move freely inside. During the winding the springs become flat occupying little space. Also, a sail material is folded between springs in the form of an accordion. During the opening the sail springs expand and take its original shape that stiffens the entire structure.

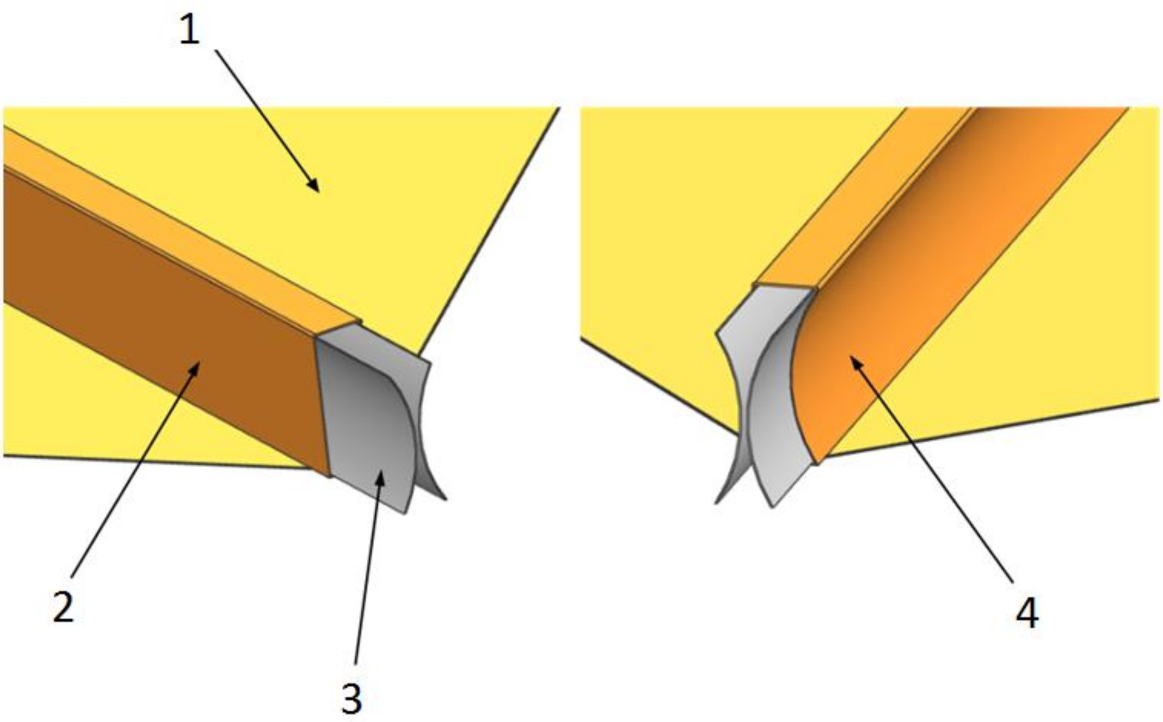

Figure 4-2 Flat springs in pocket; (1) – sail surface, (2) – springs „pocket" – unstuck side, (3) – flat, metal springs (sail arms), (4) – springs "pocket" – side stuck to one of the flat springs

Folded sail is placed in a container that enables to mount the sail inside the satellite. The sail is connected to the container by the conical spring. One end of the spring (a coil with the largest diameter) is fixed to the bottom of the container. The other end of the conical spring is fixed to the sail. After compression of the spring, a sail reel is attached (in addition) to the components of the mechanism for sail opening. This mechanism keeps the folded sail inside the tank and is responsible for opening the sail in orbit. After releasing the mechanism, sail slides out about 20 cm off the satellite.

4.1.1 Reel

The reel is an element around which flat springs are used to open the sail. Its purpose is to keep the springs stable during the entire mission and provide them with controlled deployment process. Currently tested prototype reels are made with use of a 3D printer using ABS material. The final version will be made of aluminium with SLS technology or (if it will be possible) using CNC machines. Figure 4-1shows the project of deorbit system reel.

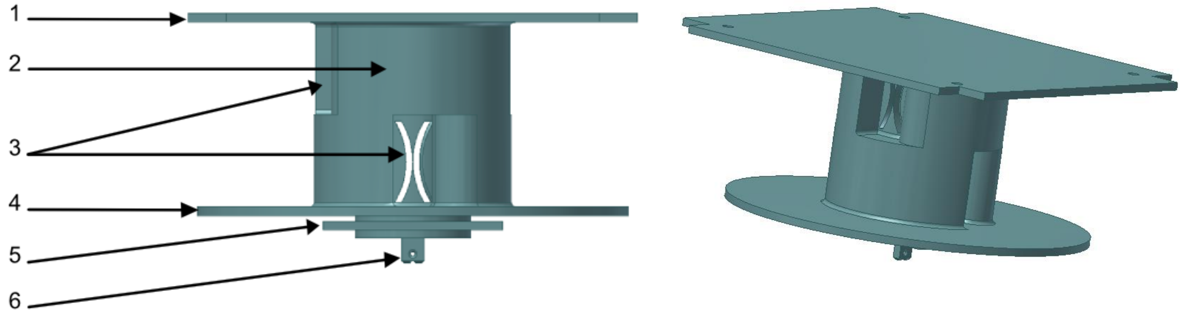

Figure 4-3 One of the deorbit system reel variants. 1) top plate (cover), 2) reel, 3) holes for flat springs, 4) bottom plate, 5) conical spring mount, 6) ear for sail release mechanism

The top plate (1) is a container cover. It is used to ensure the coaxiality of the reel and container; to maintain folded sail in the container; to keep the springs in the appropriate level during the deployment; and to lock down and separate deorbit system from the external environment. The barrel (2) having an outer diameter of 44 mm is used for mounting and winding flat springs, which pass through holes (3) having a cross section similar to the letter “X” arranged on two levels. Sail material is attached to flat springs through tight pockets and folded between top (1) and bottom (4) plates. Wide round plate (4) is used for steadily pushing the sail material out of container. Below the lower plate is a square disc (5) that is used for mounting the conical spring to the reel.

Figure 4-4 Mounting of the flat spring inside the reel.

The deformation of the flat springs has been observed during winding. The near-mounting-segment of the springs (shown in Figure 4-2) were bend on too small radius. To increase the bending radius without increasing the diameter of the reel, the project had to be changed. Currently tested shape is shown in the Figure 4-2.

Placing the “X” holes on the four arms of a reel lets to reduce its diameter and bending radius of the flat springs. Springs are now mounted inside the “X” holes with the use of a screw and glued to their inner surface. This prototype of a reel has been tested on the folding stand. Tests were successful and the sail was completely folded into 90 mm diameter.

4.1.2 FLAT SPRINGS

To deploy the sail material, two pairs of flat springs are used. When the sail is folded, springs are wound on the reel. After deploying the system with conical spring, flat springs begin to unreel. When fully deployed, they spread the sail in a plane perpendicular to the Z axis of the satellite and stiffen it, while being attached to it at two heights, as shown in Figure 4-3.

During phase B, DT made tests with different flat springs - custom made of beryllium copper and flat springs used in the production of metal rulers. Due to the fragility of the beryllium copper springs (fissures were found near reel after sail folding) it was decided to use steel springs from rulers. Such springs have been used in prior CubeSats missions and fulfilled their role. In phase C it is planned to test the springs after the removal of their paint.

4.1.3 SAIL MATERIAL

The PW-Sat 2 mission is going to test the use of 4 m^2 deorbit sail, that together with the deployment mechanism has to fit in a volume of less than 1U CubeSat. An important aspect of material selection is its low weight and low permeability. It has to collide with as many atmosphere particles as possible to increase the aerodynamic drag. The team decided to use Mylar (PET polyester film), that is a commonly used material in space applications, with a thickness of 5 or 12 μm or MLI. The flat springs are placed in Mylar/MLI pockets of the same thickness, attached to the sail surface with double-sided Kapton tape.

One problem that may occur during tests and deployment of the material is its tearing, starting from the edge. Mylar with a thickness of 5 μm is vulnerable to very low cutting forces. To prevent this problem, it was decided to protect the edges of the material with Kapton tape.

Tests are being made with the use of space blanket (Mylar, first aid blanket), due to its low price and better accessibility. Its thickness is 2-3 times greater than considered Mylar/MLI film, which allows making many folding and unfolding tests without structural failure.

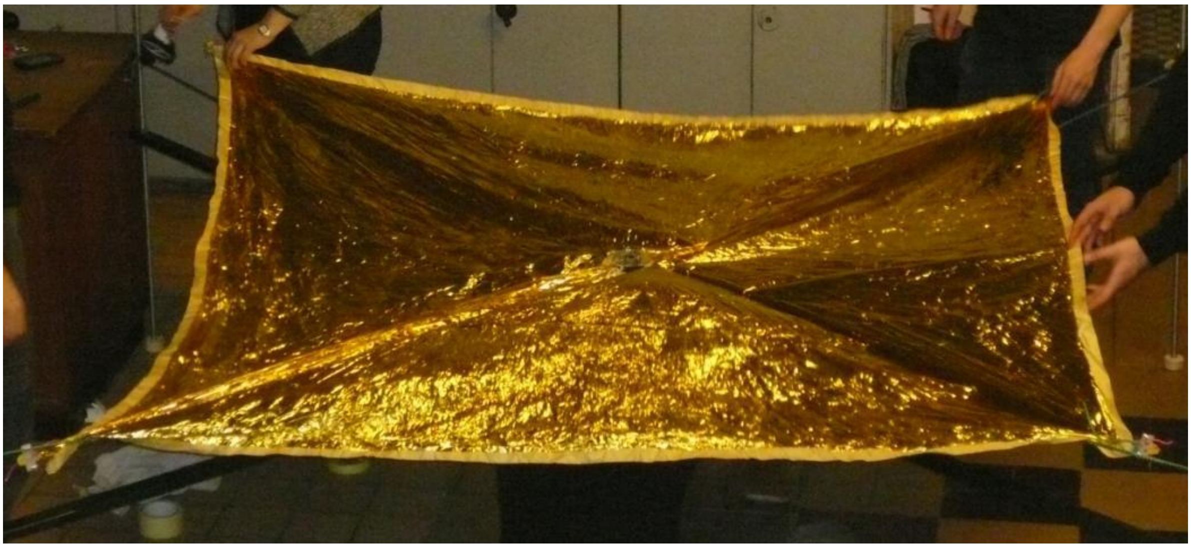

Figure 4-5 Deployed prototyped sail on a testing platform

4.2 Sail Container

Sail Container is a special element used to carry undeployed sail and protect it on the way to the orbit. It is not only important part of deorbit system but also part of satellite structure.

4.2.1 Assumptions

Sail Container protects the sail and is also durable to stresses produced by rocket acceleration during the launch and forces at the moment of sail deployment. Additionally, it needs to be the smallest as possible. The other expected feature of this element is its internal shape, which should help in deployment of a deorbit device. On the other hand, the element should be easy and cheap to manufacture using CNC technology. The material and external size must fully comply with CubeSat standard requirements.

The cover of the sail should easily unlock and open the container. It is also the part which could be used as counterweight to all systems on opposite site of the satellite to situate the mass center point in proper place. The positioning system of the cover has to be resist to vibrations and other forces.

4.2.2 PROJECT OF A CONTAINER

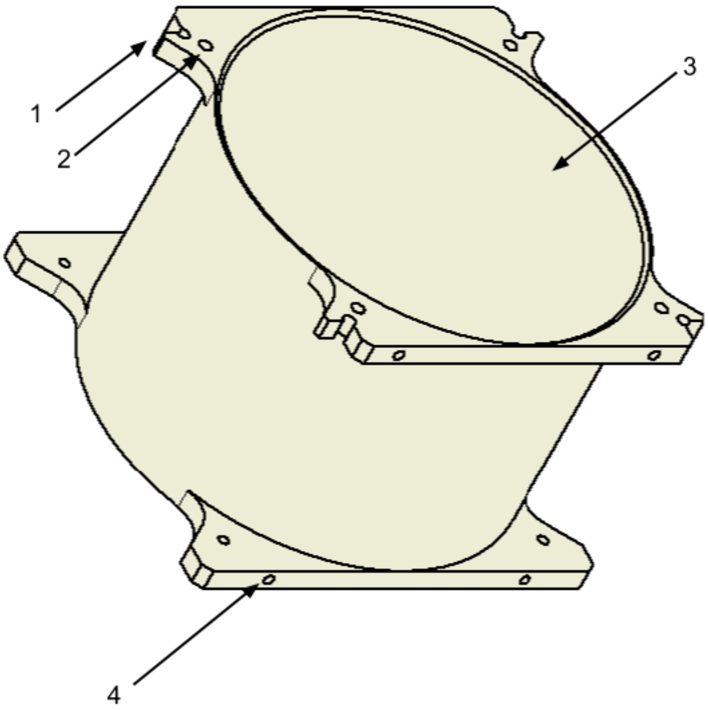

Figure 4-6 Sail container main body; 1- cutouts for rails, 2-holes for fixing the cover, 3-conical interior, 4-mounting holes

The element is a cylinder (diameter = 100 mm, height = 70mm) with two collars (outline size 100 x 100 mm) on the ends and conic internal surface. Conic shape accelerates motion of a deploying sail on spring and enlarges the probability of proper deployment of device. The slope of surface is not big – about 2°, but is better than cylindrical internal surface. In the thinnest point (top edge), the container's shell is 1.5 mm.

Collars have dual functions. The first one is connection cylinder with the rest of the satellite. Besides, they are parts of structure and stiffen whole construction – bottom collar is in the middle of frame and second – upper. There are thick enough to be drilled and screwed to mount in this holes nuts and connect element with structure, which is in corresponding places only drilled.

The bottom collar has drilled hole from that comes out the sail reel and where is locked by sail release mechanism. It also contains milled slot for spring blocking system. Sail deployment spring, which is mounted to the reel, has to be assembled to the container, too. Last coil of helix is pulled through slot and pressed by metal sheet element, screwed to the bottom of container.

Material of container and cover is Aluminum 6061.

The second part of system is a square cover, made of a sheet of aluminum. Cover is assembled to container by four rods. Beside rods' solution, geometric fit of cover and internal surface of container are also taken into consideration. In this option, cover plate is extended by conic part fitted to the slope of cone in the container. This also provides free movement only of cover in just one direction.

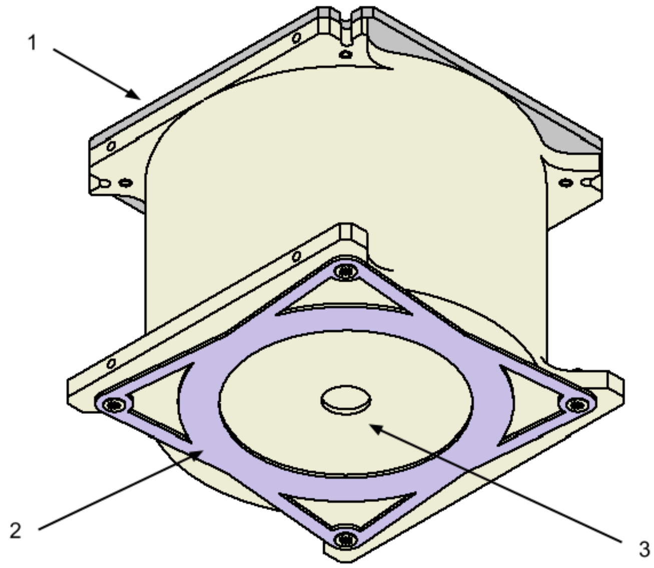

Figure 4-7 Sail container - assembly; 1- cover, 2- spring blocking system, 3 - hole for sail release mechanism

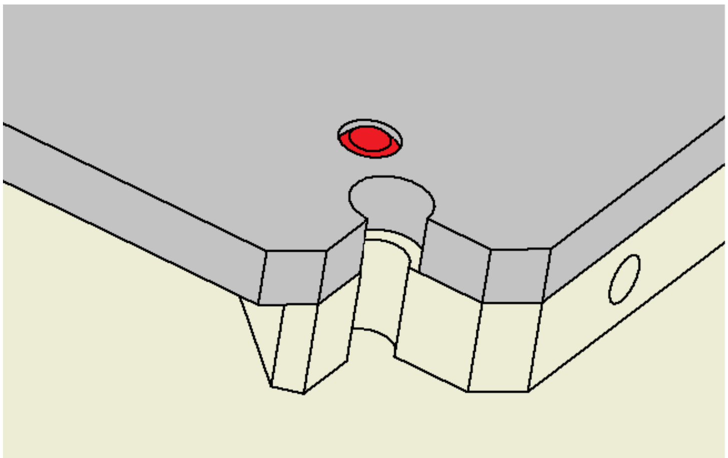

Figure 4-8 Cover fixed on container

4.2.3 MANUFACTURING TECHNOLOGY

The container is going to be produced using CNC machines. Out of thick (d = 150 mm) aluminum rod, is firstly turned cylindrical shape and then internal cone. Internal surface should be polished to minimalize friction. The shape of collars is milled using milling cutter. All corners are designed to be milled in only one mount of element in vise for each collar. Turning the whole cone from thick rod is non-economical, the element can be made from pipe and bottom instead. There are manufactured separately and welded with other parts. After all processes, holes, which are used for nuts, are drilled.

Cover can be manufactured from sheet, only corners have to be cut. Collar and cover are drilled (both parts mounted together) to get the same holes for rods. Then holes in cover are broached, because cover has to move freely in vertical direction. Cover or top surface of upper collar has to be coated with molybdenum disulfide, or other substance, to eliminate contact welding process.

4.3 CONICAL SPRING

4.3.1 THE SYSTEM STIFFENING THE CONE SPRING

The cone spring is the main element of the system pushing out the sail. Its task is to push out the sail at a distance of 30 cm from the main structure of the satellite. The sail vibrating on a spring can cause damage to other systems of the satellite and change position of satellite's centre of the gravity. It proves that it is very important to develop reliable methods of spring's vibrations dampening. One of the possibilities is to hem the spring with material and thus increase friction and decrease vibrations significantly. Moreover, it is consider to stiffen the spring by cords attached to the coils. This method was used by GOMspace in the GOMX-1 satellite's antenna [RD.2].

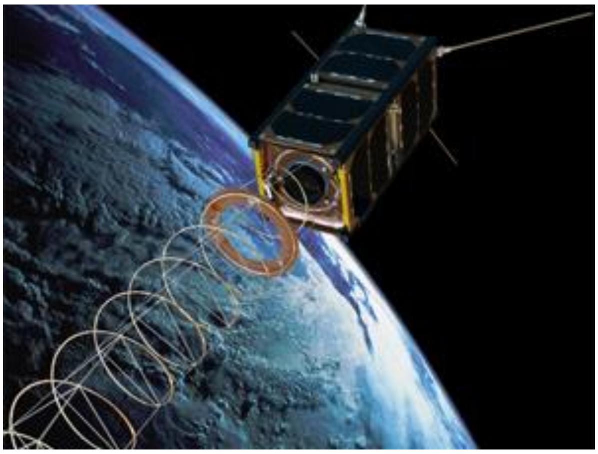

Figure 4-9 GOMX-1 with its antenna [RD.2]

This system is very complicated and difficult to manufacture. It was decided to test hemming the spring with material at first.

4.3.1.1 Material selection

Requirements:

Selected material should meet requirements for staying satellite in vacuum:

- resistance to temperature 120-150 C;
- resistance to outgassing in vacuum environment;

Different requirements determined after searching for material:

- tensile strength;
- easy to sew;
- mesh structure with proper size of "mesh".

Fibres taken into consideration:

- fibreglass;
- carbon fibre;
- polyester;
- nylon

These fibres meet the requirements set in 2.1 and have space applications. The first three fibres can be found in MLI as a scrim separator between other layers. Nylon appears in space suits and together with polyester are the most common fibres in mesh materials.

Fibreglass and carbon fibre have very good temperature resistance but it is hard to sew them. Fabrics from these fibres which have proper weighing are difficult to find. Because of above reasons DT resigns from these fibres.

Selected types of fibres

Polyester and nylon (polyamide fibre) meet thermal requirements and appear in NASA outgassing base so they could be used for hemming the spring. They are synthetic fibres with similar properties and high tenacity. Test for temperature resistance gave positive results even for 200 C. A big advantage of those fibres is their availability. They are very popular as different kinds of mesh, for example tulle and mosquito-net and it is easy to test them. Polyester has better properties and appears in NASA outgassing base as B2A Polyester Netting with TML 0.26%. It was decided to test nylon before final decision.

Table 4-1 Materials properties

Fibres	TML %	CVCM %	WVR %	Specific Gravity	Melting point [C]	Elastic Modulus [GPa]	Flexural Modulus [GPa]	Tensile Strength [MPa]
POLYESTER NETTING	0.26	0.00	0.15	1.38	250	3.5	8.3	60
NYLON MESH	3.87	0.54	2.38	1.13	216	1.6	1.3	60

Figure 4-10 Hemmed conical spring

Method of hemming the spring

Very important is to hem the spring tightly because too large amount of fabric which shows after folding the spring can cause difficulties with opening the spring. Fabric can also tangle or tear. Except tight hemming fabric should be also sewn on to each coil with proper thread. It will prevent moving the fabric on spring. Also edges of the fabric should be protected because there are the weakest points of material where threads often tear and tangle

Tests

For the first test different cone springs were used. The test shows that fabric visibly decreases vibrations. There should be more tests conducted with different fabrics and ways of hemming in order to choose the best configuration.

4.4 Sail Release Mechanism

The Sail functionality and design are partly defined by the satellite structure and other subsystems. Because of having the Solar Arrays Deployment System that works along the longer dimension of the walls, and because of the way the Sail opens, we decided to remove the Sail system outside the satellite structure. The idea is to have the Sail mounted to the conical spring, which can be folded to the thickness of only a few coils and which gives the starting force to remove the sail. During the spring stabilization the Sail structure will stay about 200 mm outside the satellite, in the -Z direction.

The aim is to create the mechanism, that will hold the sail structure until sending the signal to release it. To achieve this we have few design requirements:

- the simplicity of design – small number of parts, not complicated shapes;
- not complicated release action, needed small amount of energy;
- high reliability;
- shock resistance;
- small dimensions – to minimize the space required by the whole sail system.

At the start we decided, that we should use burning the Dyneema wire, because this requires the minimum initial power and is very simple, proven in space mechanisms many times and therefore very reliable solution. There were many ideas how to design the mechanism and we could choose from many options:

- where the mechanism should be placed: on the side of the sail's container or on the bottom and which part of the sail should be hold;
- whether it is possible to use only the Dyneema wire by passing it through one of the sail's components and stretch it with a flat spring, or whether should be used a lever mechanism, reducing the force acting on the Dyneema;
- if there will be a significant friction between parts, is it required to use starting parts besides the sail's conical spring, how should be shaped the working surfaces and what materials and coatings should be used.

After creating many computer models and discussions, there were narrowed the number of solutions to several ideas. There were made a few decisions:

- the mechanism will be placed on the bottom of the sail's container, on the opposite wall to the sail's outer wall;
- the mechanism will hold the elongated part of the sail's pin;
- the leverage mechanism will be used to minimize the risk of breaking the wire because of vibrations and relatively long time of the wire stretching;
- to burn the wire there will be used two redundant resistors, braided by the wire;
- the symmetrical mechanism will allow to divide the reacting force by two, and holding and releasing will be more reliable.

Below there are presented several ideas. The plate on the drawings is the bottom of the sail's container (Dyneema wire and starting springs not shown).

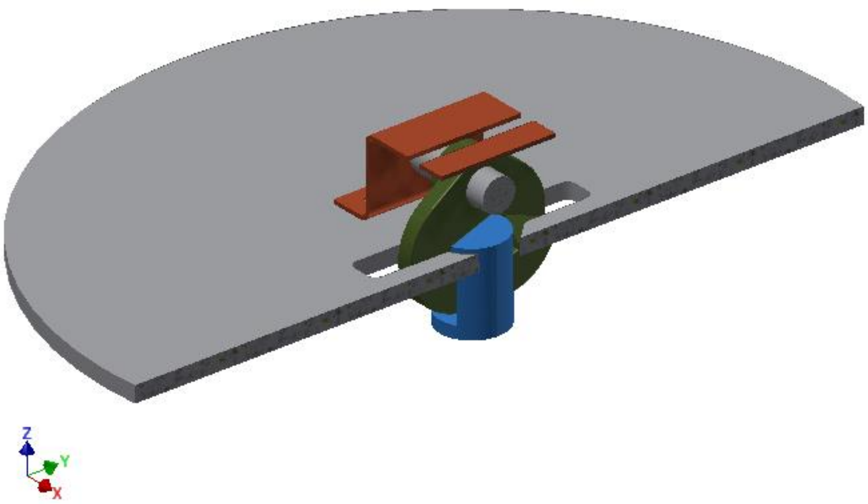

Figure 4-11 SRM - variant 1

In the first option the pin is hold by two hooks, clamped by the Dyneema wire. After burning the wire, the hooks are started with two torsion springs. It is important to minimize the friction between the hooks and the pin. The solution requires quite lot of space over the pin.

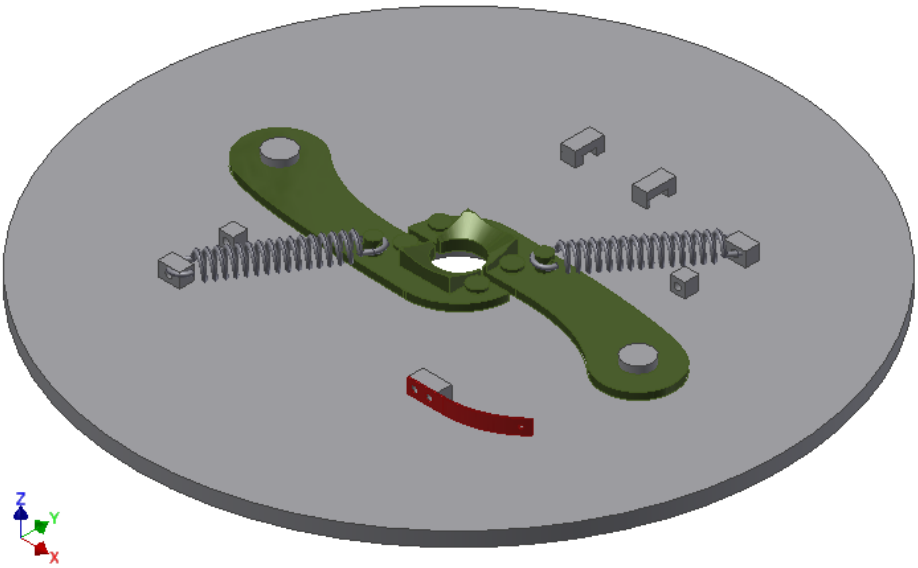

Figure 4-12 SRM - variant 2

In the second version the pin has a conical surface, that is held by two clamps moving in the surface perpendicular to the pin's axis. The Dyneema wire holds them and two flat or tension springs enforce their motion. The important thing is to minimize the friction and optimize the cone angle. The mechanism is very flat and the pin is the highest part of it. The end of pin must be wider and the pin's core must have a diameter enough to give the pin good mechanical strength.

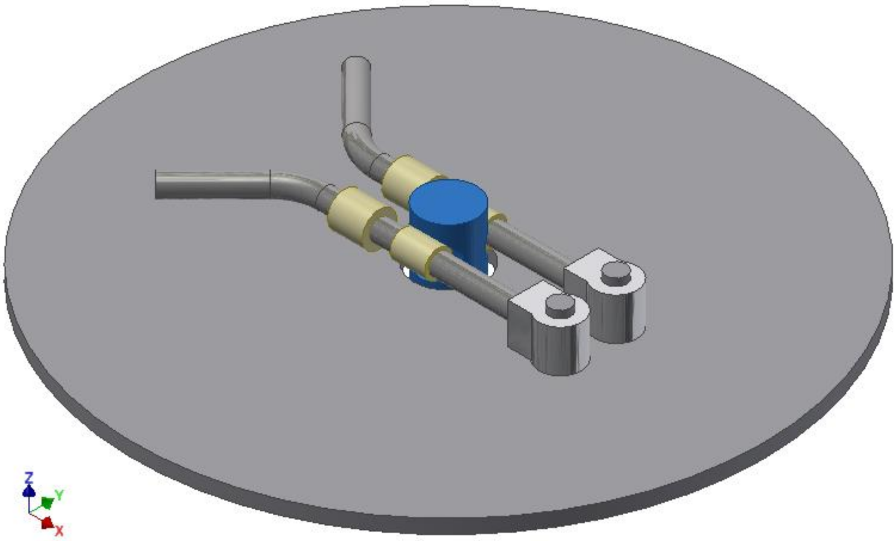

Figure 4-13 SRM - variant 3

The third option is similar, but uses two rods and sleeves to make the motion easier. The mechanism is held by the Dyneema wire and started by flat or torsion spring mounted to the hinges or to the rods' ends. The pin has to be blocked along the rods direction to minimize the lateral vibrations and the possibility of slipping out. The leverage mechanism allows to minimize the force acting on the Dyneema wire significantly.

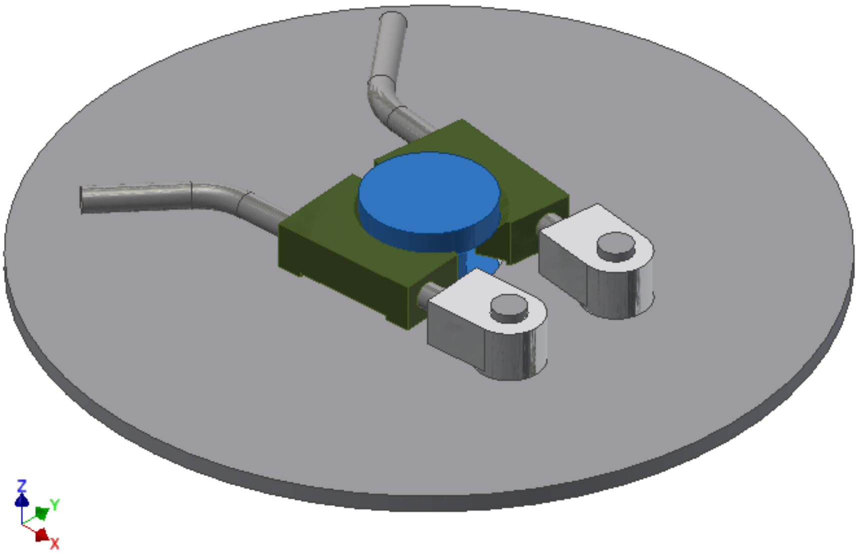

Figure 4-14 SRM - variant 3a

The last version is the combination of two earlier solutions. It does not differ much from them, but it is also worth testing.

The first tests will be performed on the 3D printed plastic parts. Later, we will initially choose the best solution, work on the components' shapes, materials and coatings and prepare the real-size and strength prototype.

4.5 THE SAIL'S ASSEMBLING STAND

The main construction requirements for that project was to design the stand allowing the correct assembly of the PW-Sat2 sail. The sail is folded properly if:

- Diameter of folded sail at its widest is lower than 90 mm
- Folded sail is roller-shaped and has no distortion
- Each material layer is placed in parallel relation to other layers
- Material layers do not tangle
- Material layers adhere to each other and do not have empty spaces between
- Sail's arms fold up on mandrel continuously, without any breaks

To achieve proper assembly of the sail a number of assumptions have to be made:

- Maximum sail's dimensions – 2 x 2 m
- Sail's arms are twisted simultaneously
- Arms are stretched with sufficient force allowing precise material folding
- Force stretching the sail's arms can be regulated
- The process of assembling the sail can be stopped at any moment
- The speed of assembling can be regulated
- The process of assembling can be reversed in order to improve the folding of the material layers
- The lowest possible number of people required to operate the stand
- Stand's highest possible mobility
- Easiest possible assembly and disassembly of the stand
- Lowest possible cost of the stand
- Lowest possible space requirements for disassembled stand

4.5.1 RESEARCH

After the first attempt of rolling the sail (600 x 600 mm) it became clear that it is too hard for one person to do it properly. Assembly of full-scale sail would be much more difficult because of necessity of more people engaged into the process – one should carry the whole sail above the head while the other one would start folding the material around the mandrel. That option seems simply impractical so it became clear that designing sail's assembling stand was crucial to the whole project.

Figure 4-15 600 x 800 mm sail (model)

Figure 4-16 Full-scale sail – 2 x 2 m

The other problem was connected with damaging process of the springs during their torsion around the mandrel. If the radius of mandrel was too small, springs were damaged while rolling the sail. On the other hand, if the radius was bigger, the sail wouldn't fit to the tray. It became clear that designing the optimal mandrel shape is also vital to the project.

4.5.2 PROTOTYPE OF THE SAIL'S ASSEMBLING STAND

Prototype version of the stand was built to:

- Check if it is possible to assembly the full-scale sail
- Measure the diameter of folded sail
- Analyse the maintenance of springs during assembly of the full-scale sail especially cooperation with the mandrel
- Test different types of sail's folding methods
- Test various types of mandrel
- Acquire experience before the final version of stand

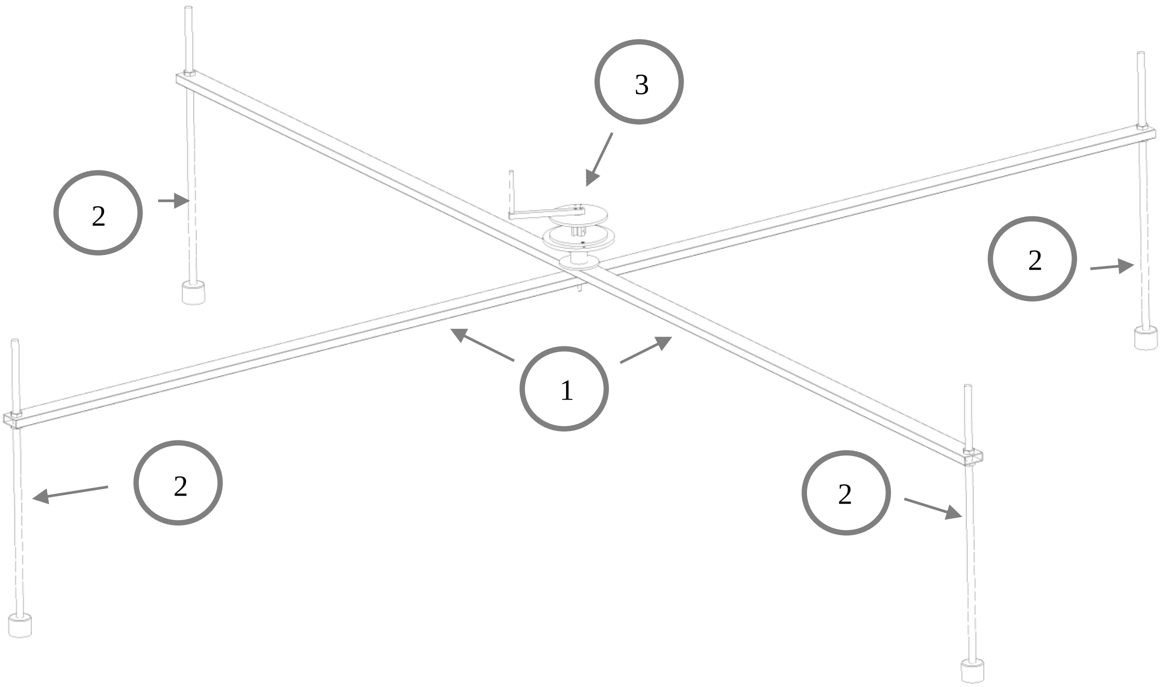

Figure 4-17 Prototype of the sail's assembling stand

The stand was made mainly from the elements which were available in Students' Space Association workshop. It was built in shape of cross with its arms made of steel profiles – 50 x 20 x 2 mm and 3.2 m length connected in the middle (1). Each end of the profile has a drilled hole that a metal, threaded, M16 pole run through (with stabilising foot at the base) (2). In the middle of the cross there is a quill with ball bearing (3). There are two small metal bars fixed to the quill which stabilize and align the mandrel (4). Arms of the sail are taut with lines (during sail's folding process (5)) which run through the pulleys fixed to poles at the end of metal profiles so it provides radial force tensioning the sail (6).

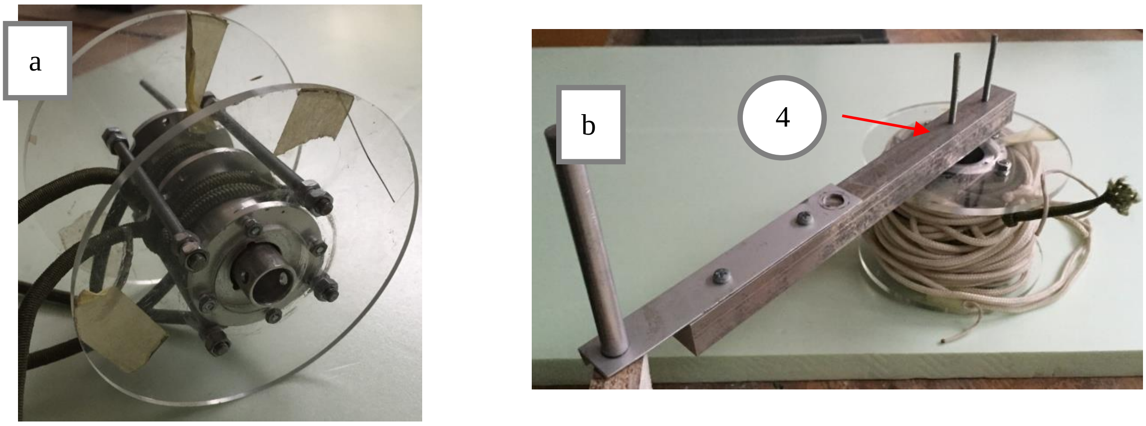

Figure 4-18 (a) Quill fixing the mandrel with the stand (b) Crank and mandrel's mounting rods

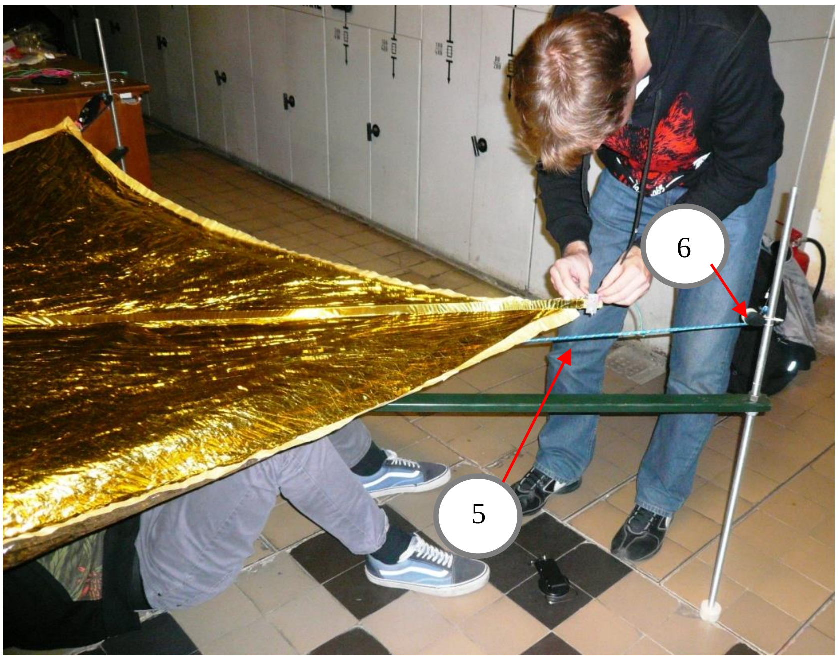

Figure 4-19 Mounting the sail to the prototype sail's assembling stand

Winding process was based on rotating the sail manually with a crank (7) while also providing constant arms orientation.

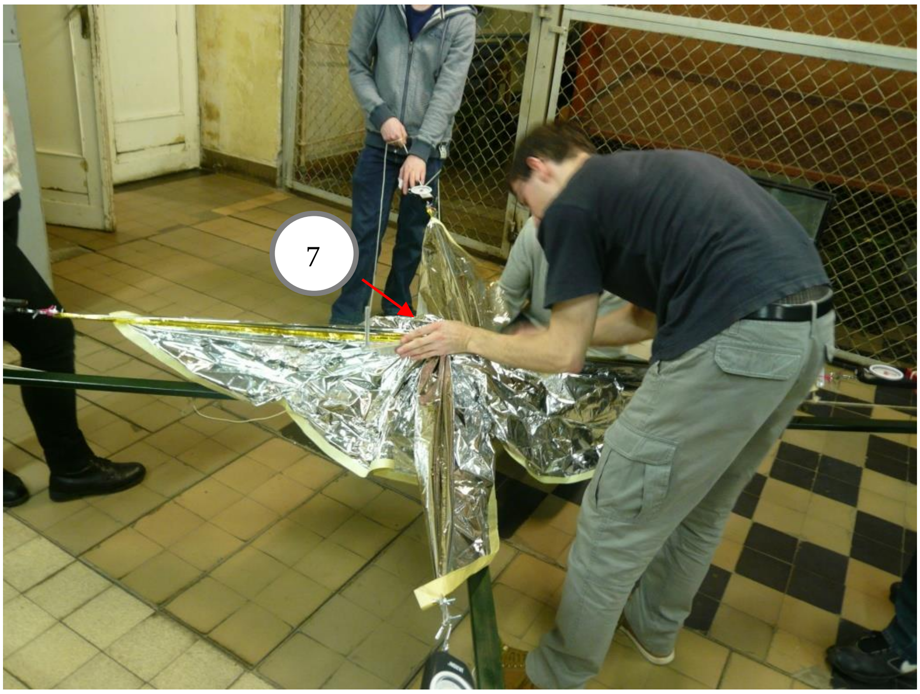

Figure 4-20 Sail's assembling and tension force measurements

4.5.3 MEASUREMENT OF THE SPRINGS' TENSION FORCE

During the first tests of the sail on the prototype stand it turned out that the lines weren't tight enough and the radius of rolled sail was 140 mm (while the goal was 95 mm). In an early phase of tests, tension of the lines wasn't controlled and it was low at the beginning and very high at the end, the sail's material was folded asymmetrically and unevenly. To control the tension and to gain the ability to obtain higher forces – the handle had to be fixed (7). It is the reason why dynamometers also had to be used. The optimal force was determined through trial and error and it was 34.335 N.

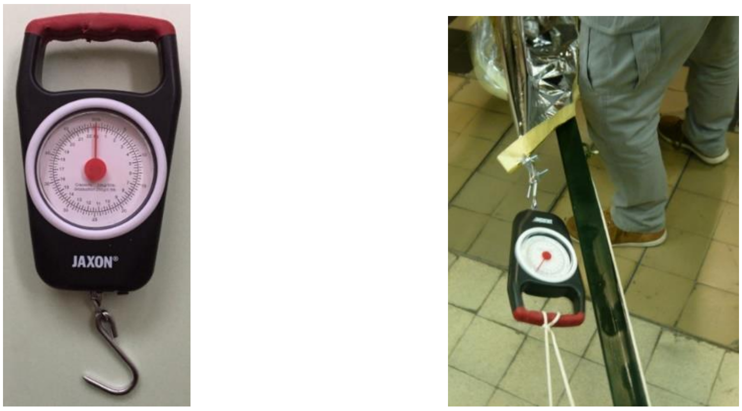

Figure 4-21 Jaxon WA120 scale and its mounting to stand's arm with the line

4.5.4 CONSTRUCTION OF MANDREL ROTATING ELEMENT

Rotation of sail's mandrel while the arms remains still is crucial to have ability to fold the sail successfully. Providing the constant tension force stretching the arms and keeping the mandrel's rotation causes the sail to wrap evenly. Main requirements to that element are:

- Mandrel's rotation should be free of any collisions (in both directions)
- Providing ability to fold the sail manually
- Versatility of construction – different mandrels application
- Simple and inexpensive construction

The mandrel is designed in a way that the flat surfaces creating the shape of a spool could be fixed to it.

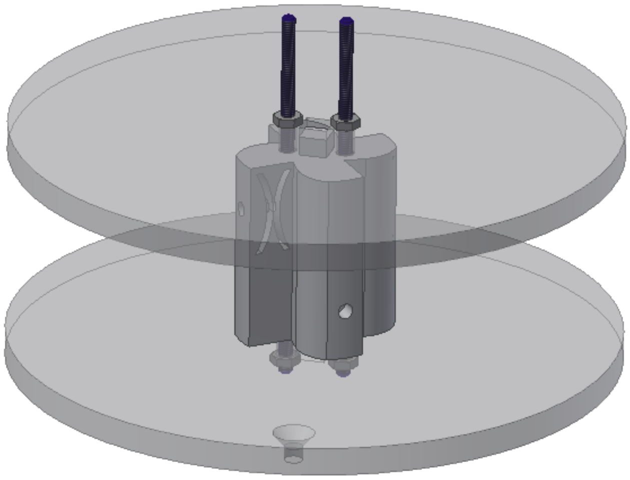

Figure 4-22 Plexiglas plates connected with sail's mandrel

That exact surfaces prevent the sail's material from tangling. They should be made of transparent material so people operating the stand have the ability to control the process of folding the sail and have vision to how close each layer of material is adhered to the others. Both plates are fixed to the mandrel with shape connection – two square-shaped grooves which shape and dimensions are similar to the holes cut in the plates. Additionally, whole element is fixed with two M3, threaded rods mounted in previously designed holes in both plates and mandrel.

Swivel connection with stand's frame had to be designed in order to provide rotation of mandrel with plates. Such connection should enable the stand's operators to easily replace different types of mandrels and remove the whole element from the sail after its assembly. Requirements are fulfilled with the project of roller bearing that can be fixed with the spool.

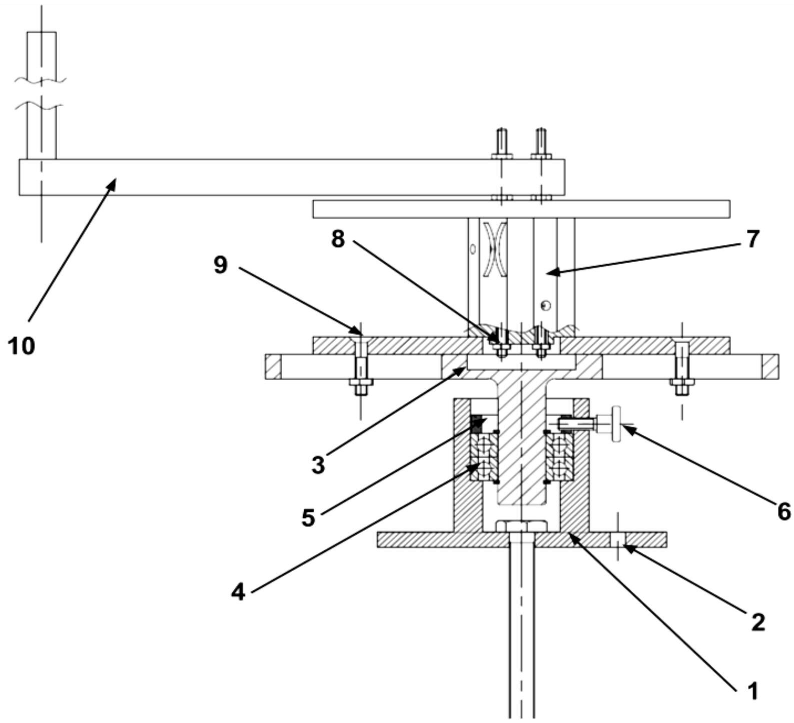

Figure 4-23 Mandrel's reel connection to mandrel's rotation mechanism

Sleeve is fixed to the stand's frame with M8 screw in the frame's arms intersection (1). Sleeve has an additional hole in its flange (2) which provides steady mounting with the frame – M8 screw runs through the sleeve's bottom and both profiles, acting as frame's mounting and also twisting the arms of the stand at the center of their intersection. A screw is placed in an additional collar's hole which also runs through one of the profiles, blocking rotation of the sleeve.

Inner side of the sleeve is designed to provide simple mounting of the shaft (3). This element contains of 15 mm diameter collar-topped (8 mm thickness) shaft. Two 6002 bearings (4) are mounted on the shaft with edging rings. Another edging ring is placed over them (5). It has a hole to mount M3 screw (6). The whole set is embedded inside previously imposed sleeve (1). The sleeve has a relief on which the bearings are rested. Bearings' movement is prevented by tightening the edging ring with M3 screw running through both the ring and the sleeve.

Round relief (32 mm diameter) is made inside the shaft's collar (160 mm diameter) hiding threaded rods (8) sticking out of the mandrel (7). Along the collar's diameter two longitudinal holes are made – 4x50 mm.

Shaft's flange and reel's bottom plate are fixed with themselves by two, M4 screws (9). In the flange, the M4 screw runs through longitudinal holes. It provides an ability to mount plates with holes made with different distances from roller's middle.

So prepared connection has an ability of free movement in both directions. To make the rotation easier there is a handle fixed on the top of the reel (10). The handle is mounted on the top of protruding threaded rods and fixed with two M3 nuts.

4.5.5 LINES' TENSIONING SYSTEM

In order to provide exactly the same amount of tension force to all four stand's lines, all of them should be connected to joint reel or linked reels. Breaking torque application to the reel should result in the same tension in every line.

To reduce the cost of rebuilding the prototype stand it was decided to use previously fixed pulleys (1). Main reel, used to wind the lines around, is located in the middle of one side of the stand (2). Lines mounted much farther from the reel run through pulleys mounted on corresponding legs and then through remaining ones (3) from where they are directed to the reel. Lines mounted closer to the reel run only through corresponding pulleys.

Figure 4-24 Assembling stand model

Folding up several layers of line would result in changing diameter of its winding during unreel process which would also result in changing tension force. It was decided to design two-reel system. Breaking torque is applied to the first of them (2) and also several layers of lines are wound on it. The rest of the lines are wound on the second of reels (4).

During sail's assembling process, breaking torque should prevent the lines from unfolding to the moment when moment of tension force would exceed it. Constant tension force requirement is fulfilled by that system.

4.5.6 CONSTRUCTION OF REELS TENSIONING THE LINES

The first reel (1) contains of aluminium circular tube (60 mm diameter, 2 mm width, 750 mm length), fixed with closed, rectangular aluminium profile 60 x 20 mm, 2300 mm length (2) which is mounted right above stabilizing feet. There is a hole in the middle of the profile through which M10 threaded rod is fixed (3). Circular reel's tube is imposed on the rod and then circular plate fragment (2 mm width, 70 mm diameter) with a hole for threaded rod, closing the reel from above (4). Whole construction is nut tightened which allows regulating reel's breaking torque. There are also four edging rings, at intervals of 50 mm, creating four separate areas for winding the lines (5).

The second reel, fixed on the rectangular profile (540 mm from the first reel), consists of M10 threaded rod with eight threaded sleeves creating four separate areas for winding the lines (7). Sleeves are mounted at determined height with nuts.

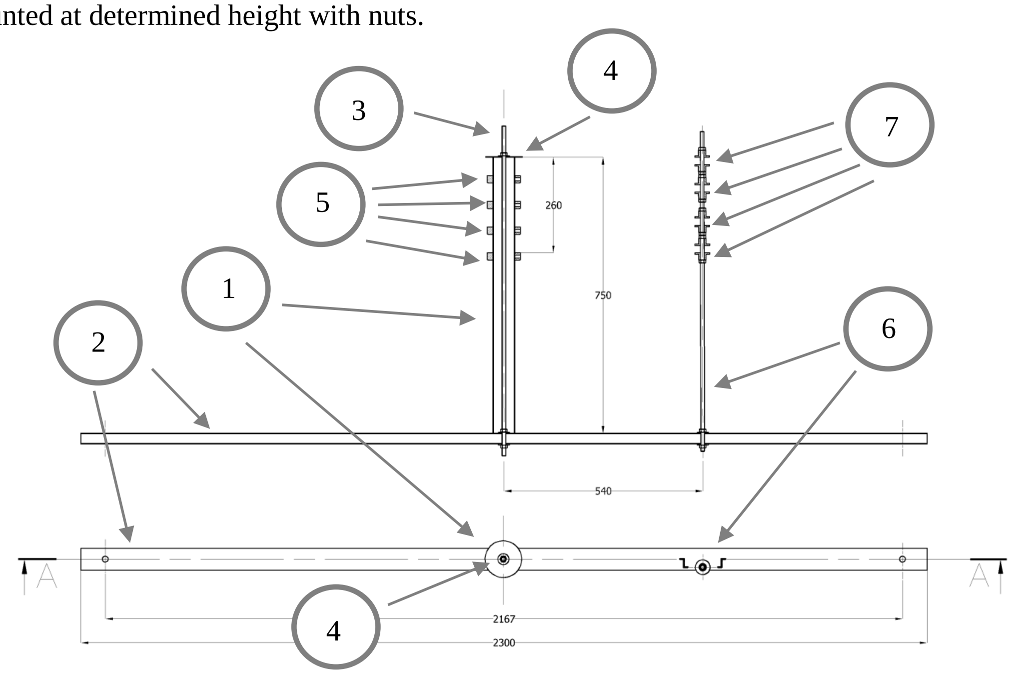

Figure 4-25 Reel's system model

5 SOLAR ARRAYS DEPLOYMENT SYSTEM

5.1 RELIABILITY

Due to the nature of space missions the subsystems on the orbit launched device must have reliability at least 98%. That is why designed mechanism should have simple construction and consist of components that individually have a high reliability.

5.2 PRINCIPLE OF MECHANISM OPERATION

One of the most reliable parts in the mechanism is a spring. Thus the project of the solar panels deploying system was based on using helical torsion spring with properly matched torque. The mechanism was designed in a way to make modifications easily, for example to change the solar panels opening angle. In this case sufficient will be to redesign the position of the hole in the part locking the panels position.

MECHANISM OPERATION:

1. while satellite launching into orbit and in the initial phase of the mission the solar panels are closed (adjacent to the walls) – Dyneema wire is attached to the free ends of the panels and immobilizes them
2. torsion springs placed in the panel's hinge are subjected to pressure (the angle between the free ends of the springs is 90°)
3. satellite receives a signal to open the panels – electric pulse is send to the resistors touching the Dyneema wire
4. resistors heat up and the wire is burned
5. torsion springs are opening the panels
6. the panels lock in position of 90° by latch - truncated cone fixed on the push spring falls into round hole
7. residual torque causes a continuous spring pressing and prevents the closing of the panels

5.3 HINGE PARTS DESIGN

In order to save the satellite side surface, the hinge structure is located inside the satellite's rail. To maintain the panels stiffness there is designed a connection of panels with the main structure by using two identical hinges. Hinges built into the rails will need to make cut-outs in the rails.

The condition of contact rails with P-POD for at least 75% of the rails surface results in restrictions of the cut-outs length in the rail:

$$w = \frac{0,25 * L}{2} = 27.1\ mm$$

where:

L – rail length = 217 mm

w – maximum width of a single cut-out

5.4 MECHANISM PARTS

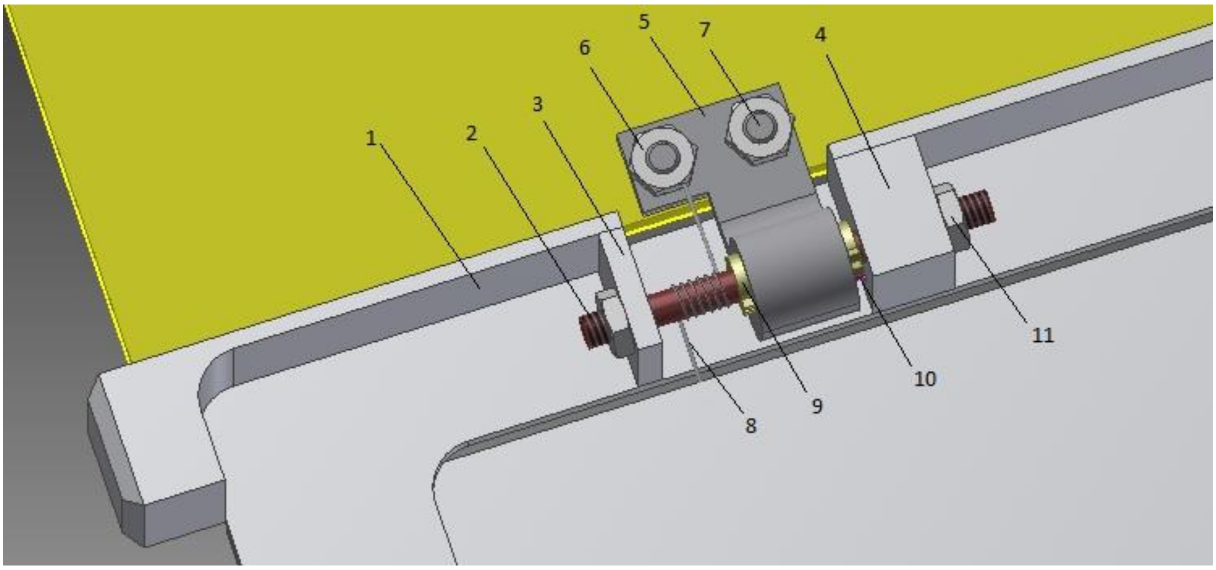

Figure 5-1 SADS – assembly

Table 5-1 SADS elements

Part no.	Part name	Quantity	Standard/document/comments
1	left/right rail	2	CubeSat Design Specification
2	shaft φ2mm	4	
3	hinge part 1 (pasted)	4	
4	hinge part 2 (pasted)	4	
5	sleeve	4	
6	hexagon low nut M2	8	DIN 934
7	enlarged head screw M2x6	8	DIN 921
8	helical torsion spring	4	
9	Seger clamping ring	8	ring under shafts without grooves
10	latch	4	
11	hexagon low nut M2	8	DIN 934

5.4.1 Rail

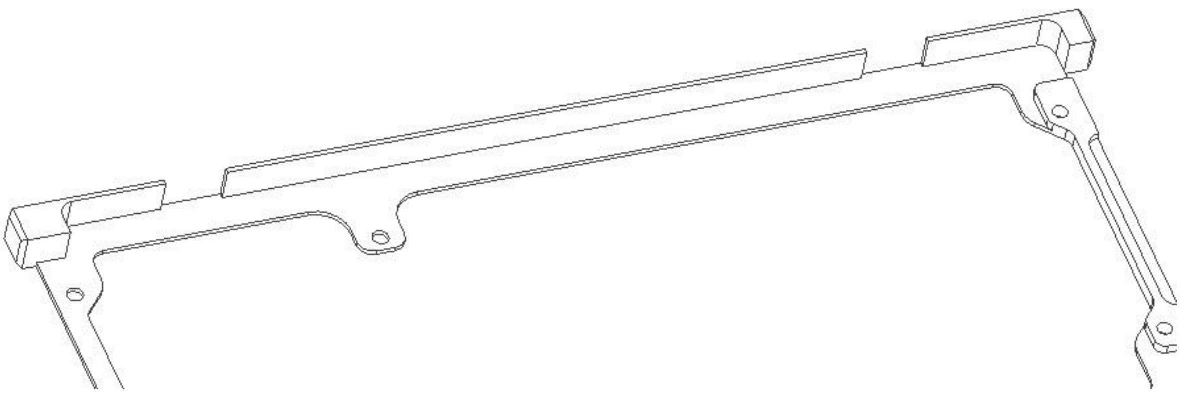

Figure 5-2 Rail - contour

Rail is made in the form of angle bar with full ends. These ends are required in accordance with the CubeSat standard, they are used for ejecting the satellites from the P-POD. The angle bar can definitely reduce the weight of the item.

In the rail there are two cut-outs with a length of 7.5 mm which allows to mount the hinge of opening panels mechanism

The rail is wholly milled – material: aluminum 7075.

5.4.2 SHAFT

The shaft performs the functions of an arbor that the hinge elements rotate around and on which the torsion spring is mounted. The elements are mounted on the shaft by normalized Seger clamping rings (the rings do not require grooves).

Shaft dimensions: φ2mm, length 25 mm.

5.4.3 HINGE PARTS 3 AND 4

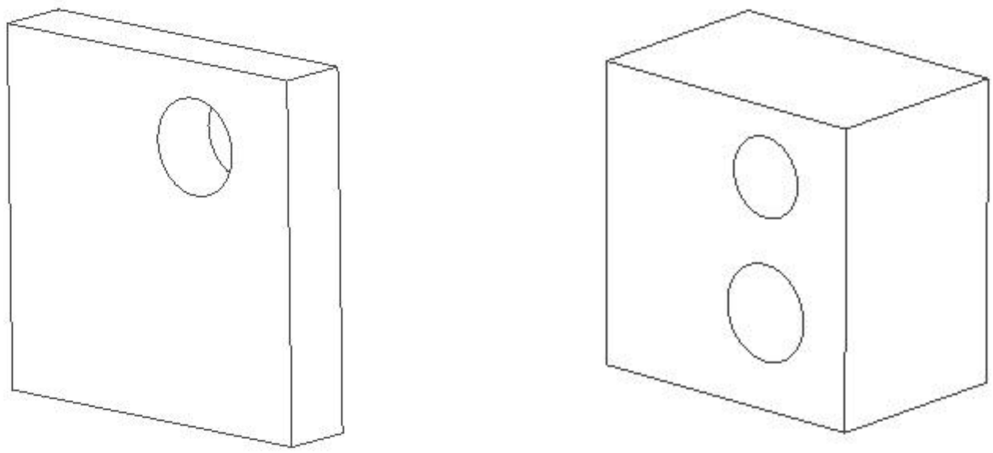

Figure 5-3 Hinge parts - contour

Both components have a through hole φ3mm to mount the shaft other hinge components. The elements are pasted to the rail's angle bar.

In Part 4, to the bigger hole falls the latch locking the panels in proper position.

The location of the bigger hole in Part 4 can be easily changed to lock the panels in a different position (e.g. 30°, which may be necessary for a specific satellite mission).

Part no. 3 and Part no. 4 material – aluminum 7075

5.4.4 SLEEVE

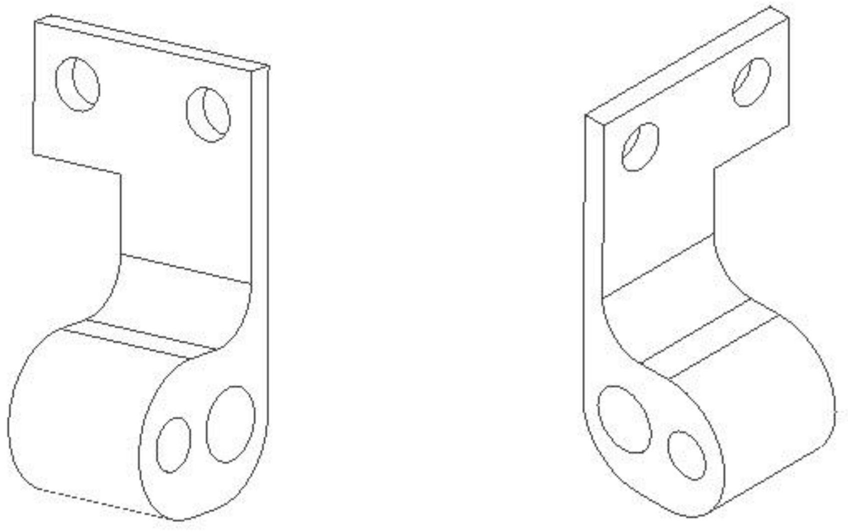

Figure 5-4 Sleeve - contour

The sleeve is the main element of hinge and mechanism locking the panels in proper position. The sleeve rotates mounted on the shaft. The latch element, fixed in the bigger hole, block the panel in the right position after a rotation of 90 degrees.

There are 2, symmetric types of the sleeve. One is mounted in the upper part of the rail and second in the bottom.

5.4.5 HELICAL TORSION SPRING

The spring causes opening of the panels. One of its free end is attached to the panel and second to satellite using stuck bent plate. The spring is made of round wire of carbon steel type According to PN- 71/M-90057.

6 SUMMARY

During phase B Deployment Team tried to execute the tasks posed in phase A and solve problems and tasks arising during operation. Plenty of Deployment Structure models were made, using a variety of flat springs, various reels and coating materials. To simulate microgravity conditions tests are held on large, flat, horizontal surface. There are planned sail tests on stratospheric balloon, during the flight at an altitude of about 30 km.

Sail container is designed to hold the sail on board the satellite. Its design stiffens the structure of the satellite and also allows to mount designed SRM .

Deployment Team designed and tested many types of conical (ejecting sail) springs. Works on stiffening the spring begun in Feb. 2015. Solar Array Deployment System were designed in order to meet emerging requirements. The system is miniaturized and simple in construction.

6.1 TASKS FOR PHASE C:

1) Deorbit sail:
    a. select the final material for sail surface
    b. order a reel made from aluminum
    c. build the final model
    d. design a connection between reel and conical spring
    e. select materials
    f. perform tests onboard stratospheric balloon
2) sail container
    a. refine the project
    b. order container
3) SRM
    a. tests of all designs
    b. choose final solution
    c. refine the shape of the elements
    d. select materials
    e. order elements
4) SADS:
    a. tests of prototypes

b. refine the shape of the elements
c. clarify the SADS position on rails
d. select materials
e. order elements

5) conical spring:
   a. refine stiffening system
   b. clarify mounting system (to container)
   c. select material
6) other:
   a. develop burning Dyneema wire system for SADS
   b. conduct FEA
7) for all:
   a. select materials for elements (included covering materials)
   b. tests of prototypes
   c. create a plan for final testing
   d. order final elements