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EXPERIMENT OF DEPLOYMENT OF PW-SAT2 SATELLITE'S DEORBIT SAIL IN MICRO-GRAVITATIONAL CONDITIONS DURING DROP IN BREMEN DROP TOWER

DROPTES 2017

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Reference [1]: *Experiment Progress Report, D. Rafalo and others, Warsaw 2017*

Abbreviated terms

ADCS	Attitude Determination Control System
DT	Drop Tower
DM	Dummy Model
ESRS	Electromagnetic Sail Releasing System
ERS	Experiment Release System
FM	Flight Model
LEO	Low Earth Orbit
MGSE	Mechanical Ground Support Equipment
RBL	Remove Before Launch
SKA	Students' Space Association
SRM	Sail Release Mechanism
TBD	To Be Defined
WUT	Warsaw University of Technology

1 INTRODUCTION

1.1 PURPOSE AND SCOPE

The objective of this document is to provide the results and all required information about the experiment of PW-Sat2 satellite deorbit sail's deployment in Bremen Drop Tower. Therefore this document contains comprehensive review about scientific background, objectives, interfaces, setup, technical drawings of the system used in the DropTES experiment.

This document was based on Experiment Progress Report [1], which was a working document according to the work plan.

1.2 PW-SAT2 PROJECT GOALS

PW-Sat2 is a CubeSat project developed by more than 30 members of Students' Space Association (SKA) at the Faculty of Power and Aeronautical Engineering at Warsaw University of Technology (WUT), Poland. The project started in 2013 and it is scheduled for launch on Falcon 9, SpaceX Company, in third quarter 2017. PW-Sat2 is a 2-unit CubeSat that carries several experiments on-board: 4m2 deorbit sail, which is the main payload, a compact Sun sensor, hinges for deployable solar panels and custom Electrical Power System (EPS). These experiments are all fully designed by project members.

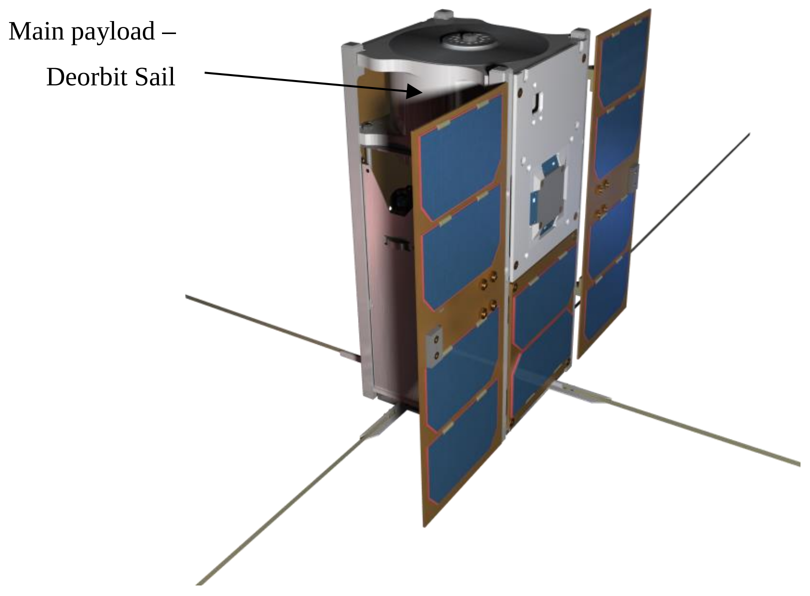

Figure 1-1 PW-Sat2 Satellite

1.3 DEORBIT SAIL

The main purpose of deorbit devices is to prevent orbital debris (satellites that completed their missions or sustained critical failure) from staying in orbit for a prolonged time, by deorbiting them. Deorbit sail is a type of a passive deorbit device (besides inflatable balloons, long tapes or tether structures) based on the drag augmenting phenomenon. The effectiveness of passive, drag-based, removal solutions decreases with altitude along with the reduction in density of the atmosphere. Deorbiting with such a device should happen faster than without due to the increased area and thus decreased mass to cross-section ratio of the satellite. There are also many other approaches to develop deorbitation systems like active solutions, which can be realized by capturing debris objects and deorbiting them with the use of drag augmentation systems, solar radiation force, electro-dynamic tether, propulsion etc.

The primary objective of PW-Sat2 is to test its main payload - the deorbit sail system - and to verify its effectiveness. This solution may be competitive for future use in small satellites with regard to system effectiveness, cost efficiency and low energy consumption..

A large number of numerous analyses performed show that the area of deorbit sail is large enough to deorbit PW-Sat2 in less than 25 years, even in case of “somersaults” in orbit random tumbling of the satellite.

The deorbit sail will be opened perpendicularly to the main axis of the PW-Sat2 satellite (See Appendix 1). In other satellites, the deorbit system could be placed in any position in the spacecraft in order to maximize the area of the material interacting with the rarefied atmosphere. This will accelerate the deorbitation process in case, when the ADCS system does not work and the satellite stays in a natural position in its orbit.

1.4 DESIGN CRITERIA

There were several design criteria taken into account during the development of the PW-Sat2 deorbit sail system.:

- mass and the envelope of the sail to be compatible with 2U CubeSat form factor,
- small volume,
- low energy consumption, a simple deployment mechanism without any motors,
- low cost of the system development (systems should be an attractive product in the future),
- high efficiency and efficient material unfolding,
- impact of the sail on the rest of the satellite, reliability, safety, maintenance load required before the launch, user friendliness and space debris generation risk,
- high effectiveness in achieving its primary objective – deorbiting small LEO satellites.

2 SYSTEM DESCRIPTION

2.1 STRUCTURE OF DEORBIT SAIL

Deorbit structure on-board of the PW-Sat2 satellite takes form of a 2 m sides square and is made of 6 µm thick aluminized Mylar film stretched across four flat springs which are attached to a custom designed reel. In the stowed position it will be wrapped around the aluminium reel and held between two limiting plates inside the cylindrical aluminium container (diameter of 80 mm). The height of the entire system will not exceed 80 mm (see Figure 2-1). After the burnout of a Dyneema fiber, the sail will unlock and will be pushed out from the container by the conical spring in a safe distance away from the satellite. During the release procedure the flat springs of the sail will expand and assume their original C-shape which will stiffen the entire sail structure (see Figure 2-2). As a result, the area and the aerodynamic drag of the satellite will be significantly increased, accelerating the satellite's orbit decay .

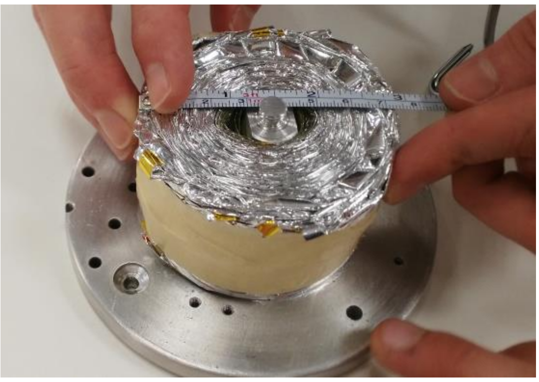

Figure 2-1 Deorbit **sail coiled around a special shaped center core of the system**

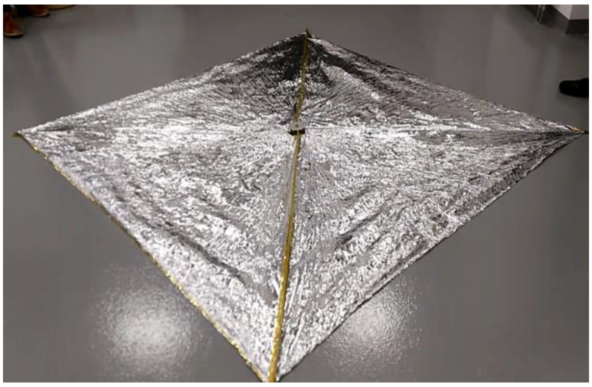

Figure 2-2 Deorbit **sail deployed on the ground**

The reel is a center core of sail around which flat springs are wrapped. Its purpose is to keep the springs stable during the entire mission and provide them with controlled deployment process. Special cuts on the surface of the main part of the reel are tailored to accommodate the shape of the flat springs. Springs are fastened in the cuts by the screws going through the reel perpendicularly to the springs. (see Figure 2-3). On top and bottom of the main part of the reel a thread has been cut to fit two plates constraining the sail material space. Top plate is used as the top cover of the sail's container, while the bottom plate separates the sail material from the container's bottom. Seeger ring holds the bottom plate, while the spring is mounted to the *conical spring mounting plate*. Arbor on the bottom of the assembly holds the bottom plate and is an interface to the Sail Release Mechanism.

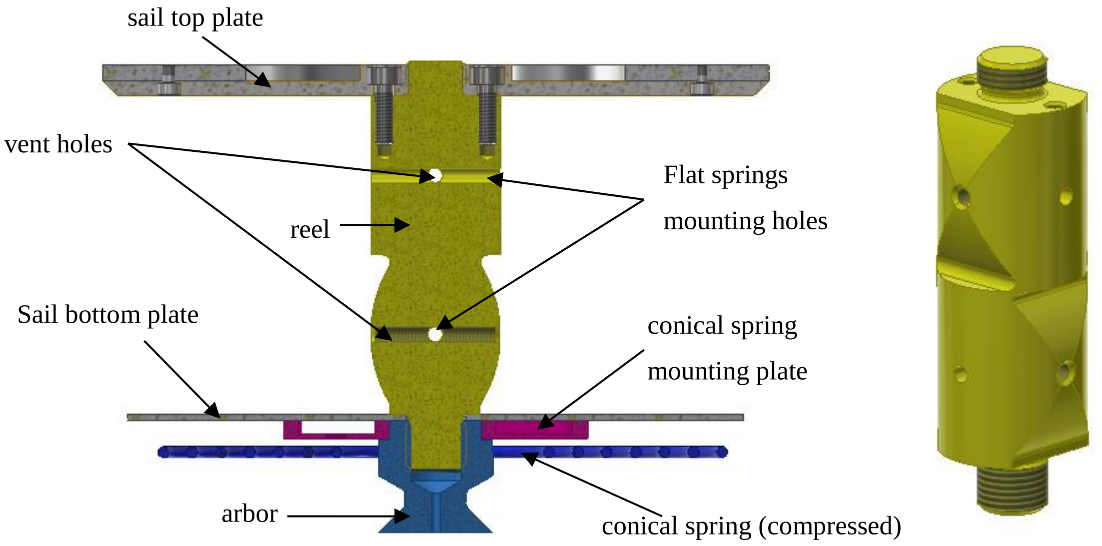

Figure 2-3 Reel subassembly cross section on the left, sail reel model on the right

By default, the reel and the arbor in flight model of PW-Sat2 satellite will be made of Aluminium 7075. In order to meet the special requirements during experiment in DT, special versions of these parts will be manufactured from steel (see chapter 4).

The C-shaped flat springs are held in sleeves made of Mylar film, each sleeve consists of two flat springs which form together the X-beam-shape. Sleeves are attached to the main sail surface along the diagonals of a square (see Figure 2-2). Such an attachment ensures that even in the case of damage to the material near the sail arms, the effective area will not change significantly. If the material was to be mounted to the arms only at certain points, then the damage to one connection could result in the loss of as much as 25% of the sail area. Arms are mounted to the reel at two different heights in order to decrease the diameter of the wrapped sail, which minimizes the volume of the whole deorbit system in the folded state.

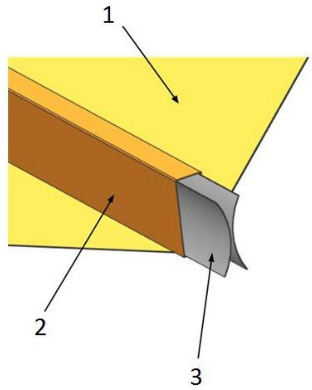

Figure 2-4 **Flat spring; 1 - sail surface, 2 - spring pocket, 3 - C-shaped spring**

Figure 2-5 **Flatsprings attached to the reel**

Folded sail is placed in an aluminium container that enables to mount it inside the satellite. The sail is connected to the container by the conical spring. The conical spring is covered with an oscillation-damping net system, and pushes the reel 200 mm away from the satellite. 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 Sail Release Mechanism (SRM). This mechanism keeps the folded sail inside the container and is responsible for the sail opening on orbit. After releasing the mechanism, sail is pushed out about 20 cm off the satellite by the conical spring.

2.2 Sail Release mechanism used in the Flight Model of PW-Sat2

During the design, the main requirements for SRM were: small volume, simplicity, high reliability, low friction, shock resistance and high efficiency. The design assumes a simple deployment mechanism without any motors. Energy is stored in the following types of springs: kick-off springs, conical spring, and tape flat springs. Particular emphasis has been put on the right choice of materials to ensure adequate reliability and system operation in space environment, e.g. to avoid cold welding of elements. Anodizing and coatings will ensure the proper work of friction pairs, such as peek-aluminum, steel-peek, and steel-aluminum.

In orbit, after the deployment command, the Dyneema fiber, which keeps the system in the closed position (see Figure 2-6) is burned through by heating resistors to a high temperature (above 150 °C). The fiber will melt, allowing the Sail Release Mechanism to release the reel and the conical spring, which is mounted to both the container and the reel. The tension of the Dyneema fiber during the storage is ensured by tension springs selected specifically for the task. Additional kick-off springs are used to support the deployment during its initial phase.

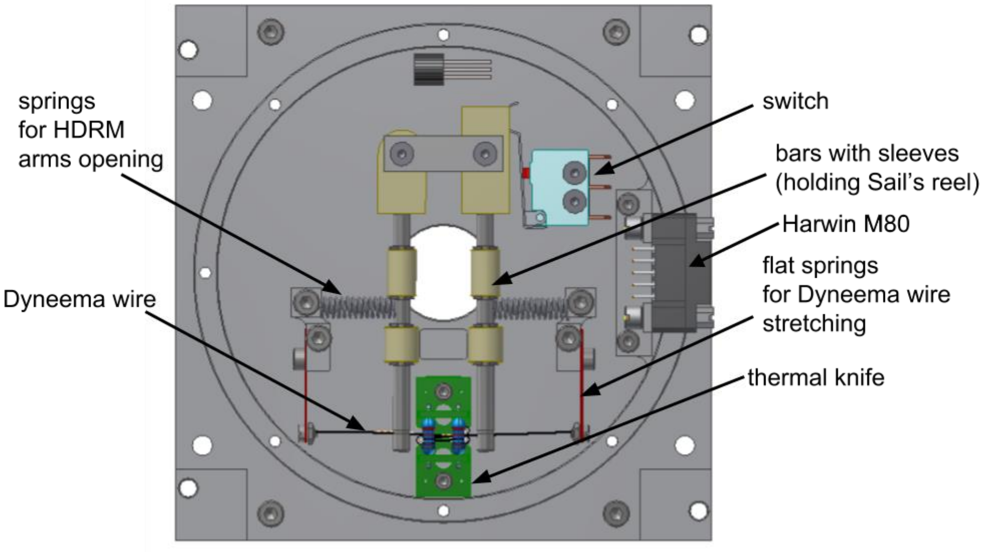

Figure 2-6 Sail Release Mechanism used in FM of PW-Sat2

The Sail Release Mechanism is based on a lever mechanism; it is symmetric and uses bushing to minimize friction between lever and reel and between lever and the mechanism sliding surface. The lever enables to decrease the force acting on the Dyneema fiber. Flat springs provide tension onto the Dyneema wire. Additional kick-off springs, as well as an inclined surface of contact with the reel, allows easy reel release. The mechanism is equipped with a switch for release confirmation and a temperature sensor, checked upon request.

The conical spring will be used only once during its lifetime, which means, there are no possible fatigue effects caused by large amount of duty cycle. The conical spring will be kept pressed under the container before releasing moment what could reduce the conical springs stiffness. In order to protect the main experiment, a conical spring is designed so that it will provide enough force to push off the sail from the container in case of losing 20% of springs stiffness.

This kind of system requires no motors and uses only the energy accumulated in the wrapped flat springs. The total electrical power used for deployment is below 2 W in time $10\ s < t < 60\ s$. For the trigger there are two redundant resistors used. One resistor is powered after another to increase the reliability. Opening of the sail is possible even in the case when the energy available on board the satellite is very low.

Additionally, in the case of PW-Sat2, the sail can be opened even after total failure of the on-board computer or lack of communication uplink. The only working system required is the EPS which is equipped with a countdown timer, triggering the sail release in case of OBC failure. Also in case of power shortage it is possible to open the sail using generated current directly from the solar arrays, bypassing the accumulators - even if the accumulators are damaged.

The default SRM used in FM of PW-Sat2 satellite was tested in vacuum-thermal chamber. The dummy model of the sail was released from the container using default SRM after 3 thermal cycles (-50°;+90°C) in the lowest possible temperature.

Therefore only sail deployment performance, which is the most critical part of PW-Sat2 test campaign, will be tested in micro-gravitational conditions during the drop. The free fall time restriction requires a redesign of SRM for purposes of the DT experiment, described in a chapter 4

3 GRAVITATIONAL RELEVANCE

3.1 SAIL DEPLOYMENT TEST IDEAS

In order to perform a proper test campaign for the deorbit sail, several options for testing have been considered, and a few of them have been performed. Seeing as how the influence of gravity is the most undesirable factor during the test, the key is to minimize its impact. The following methods have been taken into account:

1. Deployment with the arms suspended from long threads,
2. Deployment on low-friction surface,
3. Deployment during free fall from drop tower (DT),
4. Deployment on parabolic flight (PF).

The first option has been tested as the first, however it does not provide a sufficient microgravity imitation. Due to the sail deployment process, which is very dynamic and based on spinning the arms of the sail around its container, it is very hard to control the threads which are connected to the ends of the sail arms. Moreover to imitate microgravity, the relief of the sail should be equal in every point of fixation, which is extremely challenging to obtain with available facilities.

The deployment test on a low friction surface was chosen as the most adequate way to prove the experiment effectiveness on the ground. The arms stay coiled around the reel and closed in their conical container, while resting on the floor. Once the sail is released from the container, the sail arms starts extending while gliding on the floor.

The two last options will provide the closest approximation to on-orbit microgravity conditions. Although, Parabolic Flight equipment does not allow to perform the test in vacuum. Furthermore, disturbances caused by airplane movement will interfere with dynamic behaviour of sail during its deployment.

3.2 SAIL DEPLOYMENT TEST PERFORMED ON THE GROUND

The testing of the space devices, especially deployable ones is always the most time consuming activity during the space related projects. In case of PW-Sat2 project tests of deorbit sail deployment have taken lots of hours. Standard solar sails deployment mechanisms use motors and booms, it is easy to predict the behavior of the mechanism in space on the basis of test on the Earth. Mechanism designed by members of PW-Sat2 project uses flat spring what causes very complex dynamics, deployment lasts less than 0,8 second and strongly vary on environmental factors like gravity, friction of surface on which deployment takes place, moment of inertia of covers.

A large number of tests on the ground on low friction coating have been done until now, which was supposed to approximate the microgravity environment. This test cannot show the real behaviour of the system in space. Gravitational forces acting on all parts of the sail cause drag between the ground and the sail material, which does not allow for observing the effects of the sail deployment as it will on orbit. Due to the sail dimensions, the gravity influence on the sail deployment is significant while testing on the ground. Therefore the sail opening test must be performed under the highest quality conditions of weightlessness in order to get reliable results of the effectiveness of the system.

Lots of tests in different environment have been performed to find out the influence of each aspect on the Sail deployment. More or less 25 exact models of Sail have been built for testing purpose. The effort of the Team was concentrated on eliminating gravitational influence on deployment. It was considered several types of surface on which tests were performed. Team's endeavor was focused on lowering the coefficient of friction between the sail surface and surface of the ground, to minimize influence of gravity on deployment of sail. Ground was covered with special polish paste and sail's core was put under the ground to reduce contact surface.

To get knowledge of maximum level of accuracy detailed procedures of production, folding and testing were created, dedicated stand to sail folding was built as well. Intensive testing has lasted almost one year and was carefully registered. After each test session all information about test and implications from it were written to constantly develop the design and to get maximum information in the most effective way.

Thanks to the tests, sail design has been developed, and lot of knowledge about its deployment dynamics was obtained. Interesting relationship between sail covers' momentum of inertia and deployment effectiveness was observed.

Sail has been even deployed twice during stratospheric balloon flight, but the strong wind and some technical issues caused the fails.

4 DROP TOWER EXPERIMENT DESCRIPTION

4.1 HARDWARE USED IN EXPERIMENT

For the purposes of this experiment a PW-Sat2 satellite dummy model was manufactured. (see Figure 4-2, Figure 4-2). This model included the container with folded deorbit sail assembly and sail releasing system. As additional equipment a GoPro Camera was used, which was supposed to film the sail's release from the satellite's view. The size and weight of DM corresponds to the values of PW-Sat2 FM.

According to the short duration of free fall of the sail experiment conducted in deceleration chamber, it was decided to release the sail deployment using an electromagnet, which reduced the time of the sail deployment trigger. Table 4-1 Electromagnet ITS-MS 3025, Intertec Components GmbH presents the description of the electromagnet to be used in the experiment (see also Appendix 3).

Table 4-1 Electromagnet ITS-MS 3025, Intertec Components GmbH

Supply voltage, DC	Power	Force	Lifting force	Mass	External dimensions
24V	3,8 W	100 N	10 kgf	103 g	Ø30 x 25 mm

The conical spring pushing out the sail from the container generates the force of 20 kN. The conical spring, covered with net, will pull out the sail assembly, that weighs about 530 g. The sale assembly is show in Figure 4-3.ok

Table 4-2 Mechanical and electrical interfaced used in DM of PW-Sat2 Satellite contains all needed information about hardware, mechanical and electrical interfaces used in DM of PW-Sat2.

Figure 4-1 The dummy model of the PW-Sat2 satellite manufactured on purposes of DropTES campaign

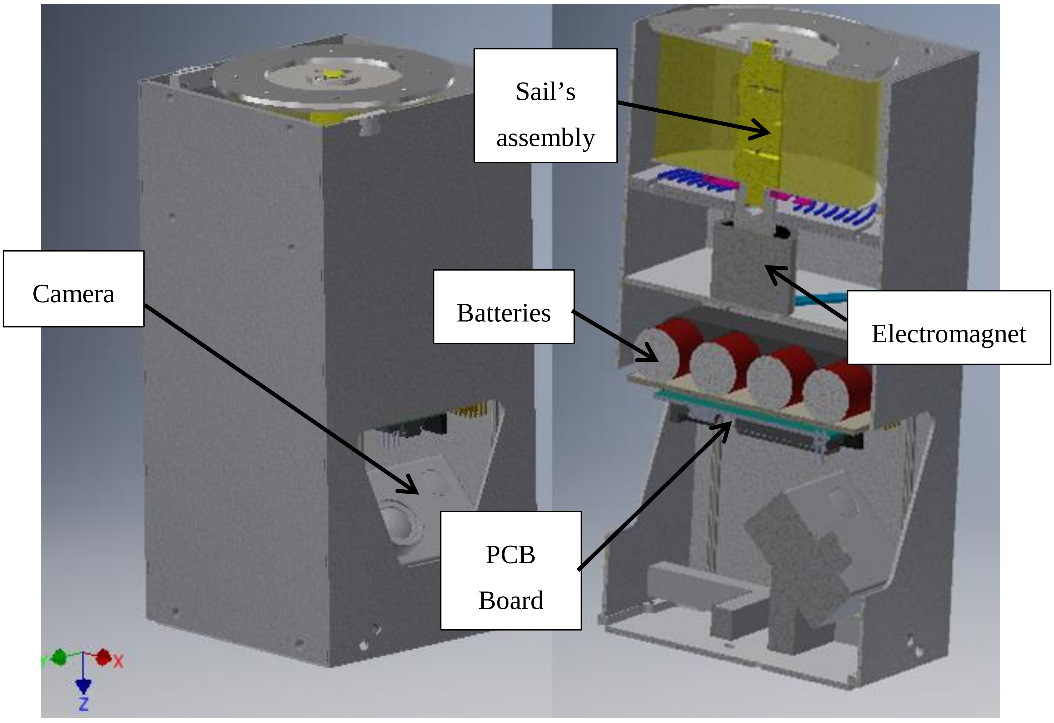

Figure 4-2 Dummy model of PW-Sat2 satellite used in DT experiment

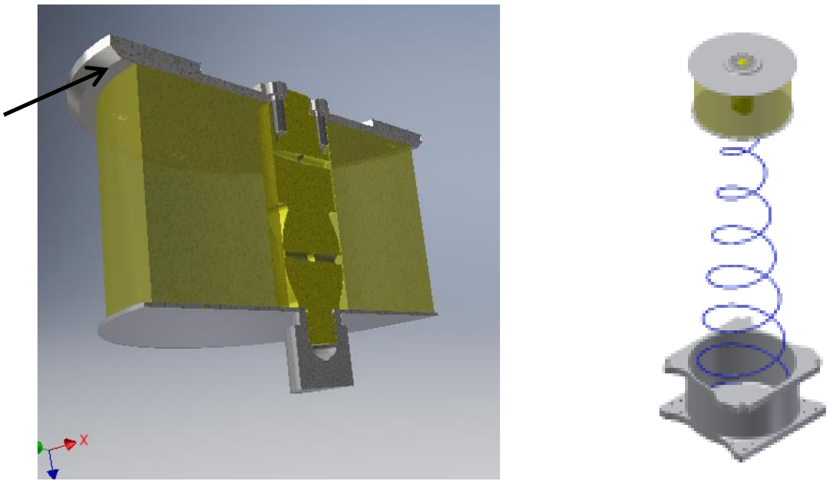

Figure 4-3 Deorbit sail assembly (on the left); sail assembly pushed out from the container (on the right)

Camera lens were mounted in a similar way as it have been done on the flight model of PW-Sat2 satellite and included in its field of view the unfolding sail only partially. Regarding limited space for the camera inside the DM, it was decided to mount a lens with 76° field of view, the same that will be used in FM of PW-Sat2. The area of the sail that is visible on the DM is presented in the **Błąd! Nie można odnaleźć źródła odwołania.**4. The idea of mounting the camera outside the DM (on the extension arm for example) or mounting was also considered, but that would cause an additional moment of inertia. It was decided to avoid lateral movements during the fall.

During the preparation week in ZARM Institute and pre-tests performed in deceleration chamber it turned out, that the GoPro Cameras xdo not have enough power capacity to withstand the duration of one drop sequence in low pressure (20 Pa). 3 models of GoPro cameras have been tested.

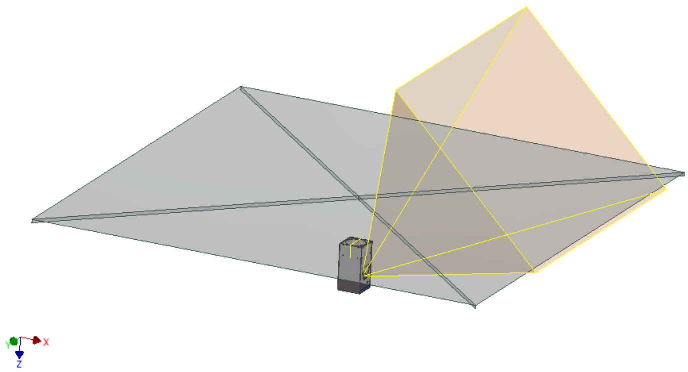

Figure 4-4 The sail's visable area from the camera mounted on-board DM

Table 4-2 Mechanical and electrical interfaced used in DM of PW-Sat2 Satellite

Part	Mass [g]	External dimensions [mm]	Quantity	Drawing / Datasheet	Provider
			Electrical hardware		
PCB board	~50	70x55x15	1	TBD	TBD
Power transistor		5x6,2x1,75	1	Transistor_IRF7416.pdf	TBD
Signal transistor		3x2,5x1	1	Signal_transistor.pdf	TBD
DCDC converter for an lectromagnet		3x3x1,45	1	MT3608_power_supply_converter.pdf	TDB
Microcontroller		18x22x10		Arduino_Uno_Rev3-schematic.pdf	PW-Sat2 Team
Harness	~50		TBD		TBD
Battery pack	178	Φ34.3; height 61,2	TBD	Hawker Energy Cyclon D 2 V.pdf	PW-Sat2 Team
Electromagnet	130	Φ30; height 25	1	Electromagnet ITS-MS 3025.pdf	PW-Sat2 Team
kill- switch	~5	TBD	1	TBD	TBD
RBL switch	~5	TBD	1		TBD
Camera	70-150	41x59x21/30	1	TBD	DT
			Mechanical hardware		
Sail assembly	530	folded: Φ80, height 70	1		PW-Sat2 Team
		unfolded 2000x2000x70		PW-Sat2-C-10.02-CONF-MICD-Drawing.pdf	PW-Sat2 Team
Container	253,2	95x97x52	1	PWSAT2-DT-SAIL-P-01.10 [Container].pdf	PW-Sat2 Team
Conical spring	24	Φ26- Φ31, height 300	1	PWSAT2-DT-SAIL-P-05.01 [Conical Spring].pdf	PW-Sat2 Team
dummy satellite (total mass)	**2600**	**100x103x205**	1	Assembly1-1.pdf	PW-Sat2 Team

5 DROPTES CAMPAIGN

Between 21st November and 2nd December 2017 four students participated the DropTES Campaign at Bremen Drop Tower. During the first week students in collaboration with ZARM supervisors were preparing the experiment releasing mechanism. In the second week, four fully deployments of the real size deorbit sail have been performed and registered by high speed.

5.1 EXPERIMENT DESCRIPTION

After discussing with DT supervisors it was decided, that the sail deployment of the sail from a freely falling object (dummy model of a satellite) would be the best solution for purposes of testing deorbit mechanism (almost demonstrating the condition in orbit). Within DropTES campaign students had a chance to perform 4 drops of their experiment. Therefore 5 folded deorbit sails (one additional backup sail) have been prepared. In order to get the most reliable results of the experiment and to ensure the repeatability, all those 5 sails have been manufactured according to the procedure of the assembly and integration of the PW-Sat2 flight deorbit sail and using the same facilities (e.g. folding stand) and human resources.

One dummy model of the PW-Sat2 satellite and 2 conical springs have been also prepared on purpose of the experiment series. After each drop DM was disassembled and the new sail was mounted inside.

The DM of PW-Sat2 satellite was mounted at the handrail on the top of the deceleration chamber. It was released from the height of about 8 m. The sail was deployed in upwards direction as shown in *Appendix 1*. To avoid the lateral movements of DM during the fall a centred mechanical interface on top of the satellite was developed.

The deployment of the sail from DM during free fall was supposed to take place after passing the handrail of the deceleration container. Therefore, a micro-controller was required to control this timing of the sail deployment. On-board of DM a gravity sensor, i.e. accelerometer (controlled by an Arduino) has been used in order to detect free fall and therefore to trigger the sail's release (after passing the handrail in deceleration chamber) and to provide the data for further analyses. The ADXL34 accelerometer was used. For free fall detection parameters *freeFallThreshold* (sensitivity of detection) and *freeFallDuration* heve been set. Also *freeFall* parameter provided information, if the device is falling down or not.

All data from the accelerometer has been logged to a file on an SD card. For this purpose a number of tests with the standard Arduino SD handling library and an SD card adapter connected via SPI interface have been executed. As a result, it was decided, to combine the speed of the SdFat library (3rd-party SD library) and the convenience of the CSV file format, which takes only 5 milliseconds, to write the data in one loop.

The code can be found in Appendix 13.

5.2 EXPERIMENT ON-SITE PREPARATION

From the first day of DropTES campaign, students and ZARM supervisors focused on the preparation of the experiment releasing system (ERS), which first version was manufactured by ZARM supervisors. After many tests it was decided to mount an experiment on a plate, which was able to be moved down and aside using electric and pneumatic actuator. The experiment (DM of the satellite) has been hanged on the ERS using a Dyneema wire, which was held by a pneumatic actuator. In order to assure the reliability of holding stand, satellite was remaining on the plate during the depression of the air from deceleration chamber. After achieving 20Pa in deceleration chamber the plate was moved down and aside on command from the console room. After cessation of oscillation movement of the DM, the third command was sent to release and drop the satellite.

Figure 5-1 Experiment Releasing System (ERS) – DM of the satellite is hanging on the Dyneema wire and standing on the plate

Figure 5-2 ERS – the plate in a down possition, DM is hanging now an a wire

Figure 5-3 ERS – the plate moved to the side

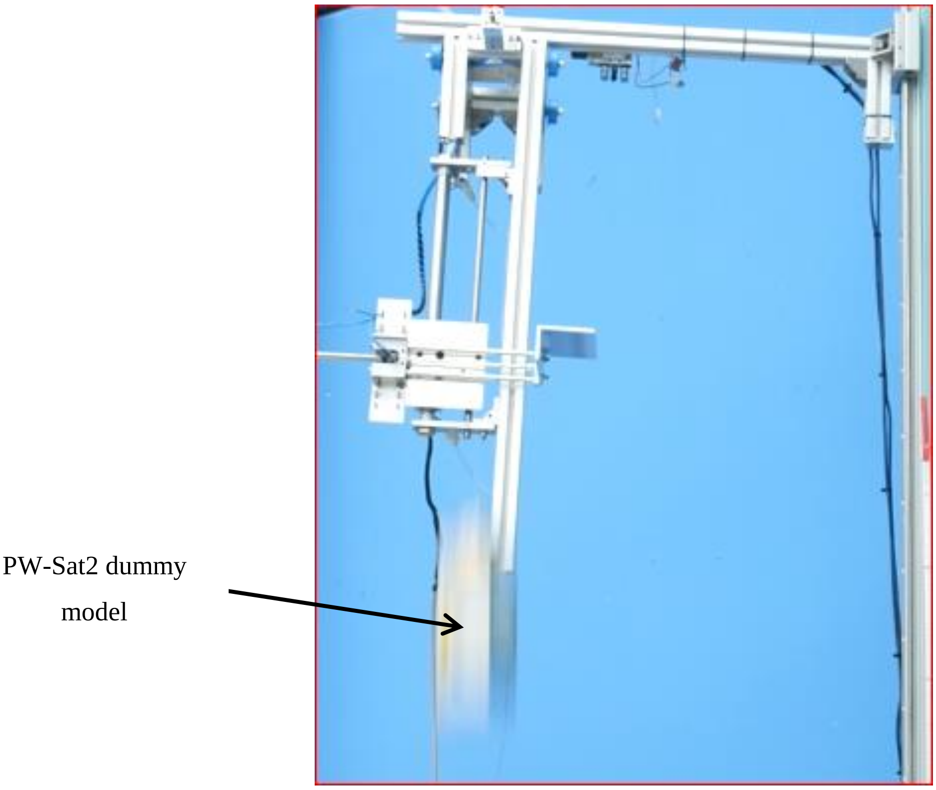

Figure 5-4 ERS after relasing the satellite

The experiment releasing system in his final configuration (see figures from Figure 5-1 to Figure 5-4) was mounted on the handrail in deceleration chamber of the high of 8 meters.

Figure 5-5 Mounting the ERS on the handrail of deceleration chamber – on the right picture the secure mesh and the secure "pillow" are visable

On the pictures below the sequence of one drop has been shown – after detecting the free fall and passing by the handrail, the sail assembly is being pushed out from the satellite.

Figure 5-6 ERS mounted in deceleration chamber – pictures taken during the test of ERS

During the experiment on-site preparation week 4 high speed cameras have been mounted in deceleration chamber.

Figure 5-7 The view of high-speed cameras during the mounting of cameras in best spots

In order to simplify the experiment's results analyses, a scale net was also mounted in the background.

Figure 5-8 The scale net mounted in the background

5.3 One drop sequence

Each drop sequence consisted steps below:

1. Mounting a sail in the container of the DM
2. Turning on the batteries on the DM
3. Mounting the DM of PW-Sat2 satellite at the handrail of deceleration chamber
4. Outgassing of the deceleration chamber (goal: 20Pa)
5. Moving down and aside a plate of the ERS (command sent from the console room)
6. Releasing the DM from the handrail (command from the console room, when oscillation ceased) , starting the countdown.
7. Releasing the sail deployment after passing the handrail (accelerator recognizes free fall, timer counts 430 ms and the power supply to the electromagnet holding the sail in place is cut off, sail is pushed out from the dummy satellite).
8. Drop of the PW-Sat DM on the net mounted above the floor.
9. Data recovery from the high-speed cameras and first analyses of the movement of the deploying sail
10. Increasing the pressure in deceleration chamber
11. Bringing out the DM of the satellite from deceleration chamber and inspection of the sail, conical spring and the DM, removing the unfolded sail.
12. Data recovery from the SD card mounted on DM
13. Charging on-board accumulators.

5.4 The results of the experiment

During the second week of DropTES campaign 4 proper experiments have been conducted and 4 fully deployments of the sail have been registered on high-speed cameras. This prove, that the deployment mechanism of the sail designed by students is able to fully deploy the $4m^2$ sail in conditions of microgravity and decreased pressure.

Conducting the sail opening experiment during free-fall from the Drop Tower in conditions of decreased pressure (20 Pa) had important meaning for the PW-Sat2 team because it allowed for final verification of the efficiency of the sail opening system before delivering it to Earth orbit.

Therefore, fully tested mechanism will be placed on orbit and its influence on the lifetime of the 2U CubeSat will be analysed.

5.4.1. First drop in vacuum

On the pictures below the movement of the sail deployment is shown from 2 points of view.

The curves of the sail's arms visible on the images taken by front cameras are caused by the low pressure of 20 Pa in the deceleration chamber.

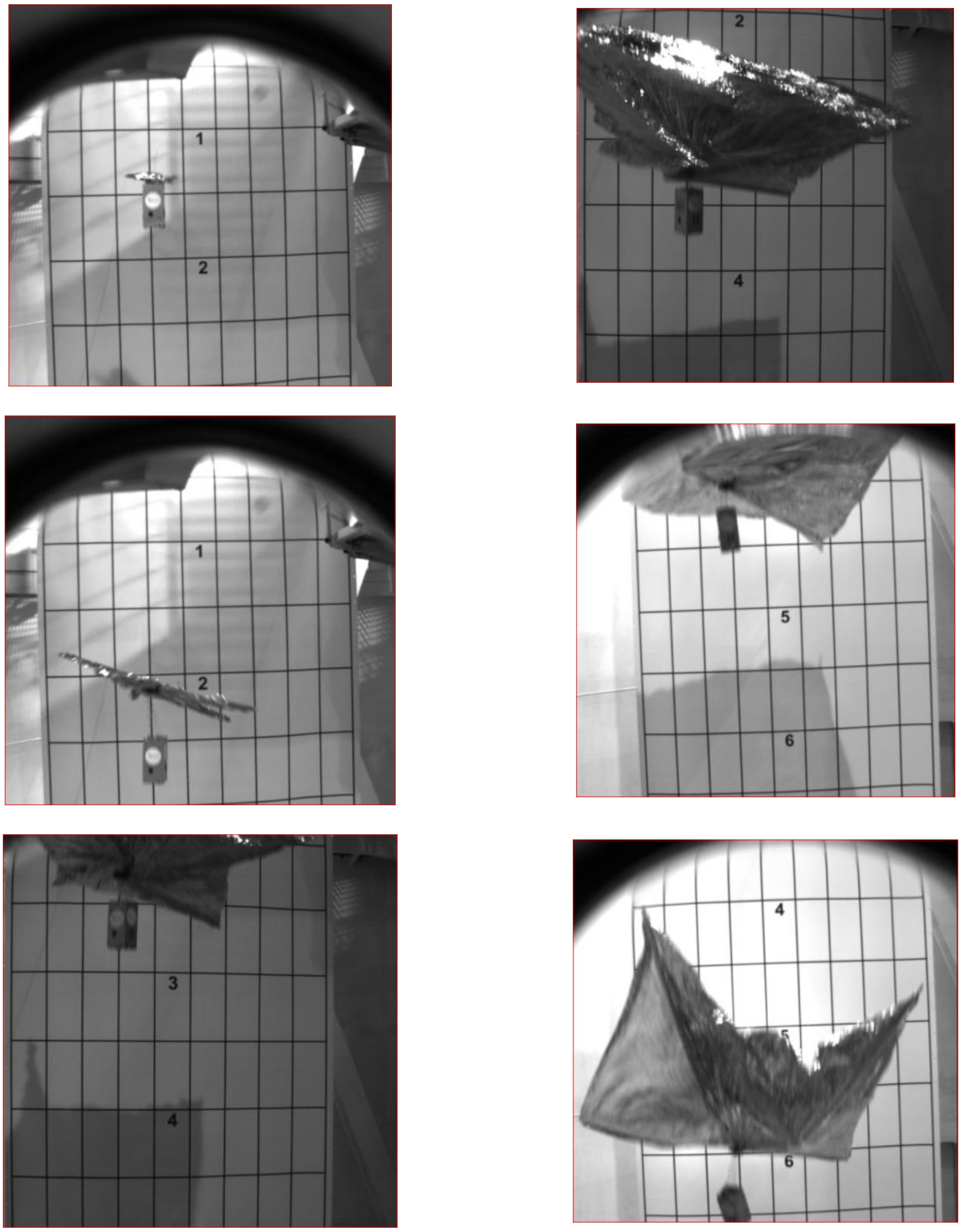

Figure 5-9 Images taken by three side-cameras during the first drop

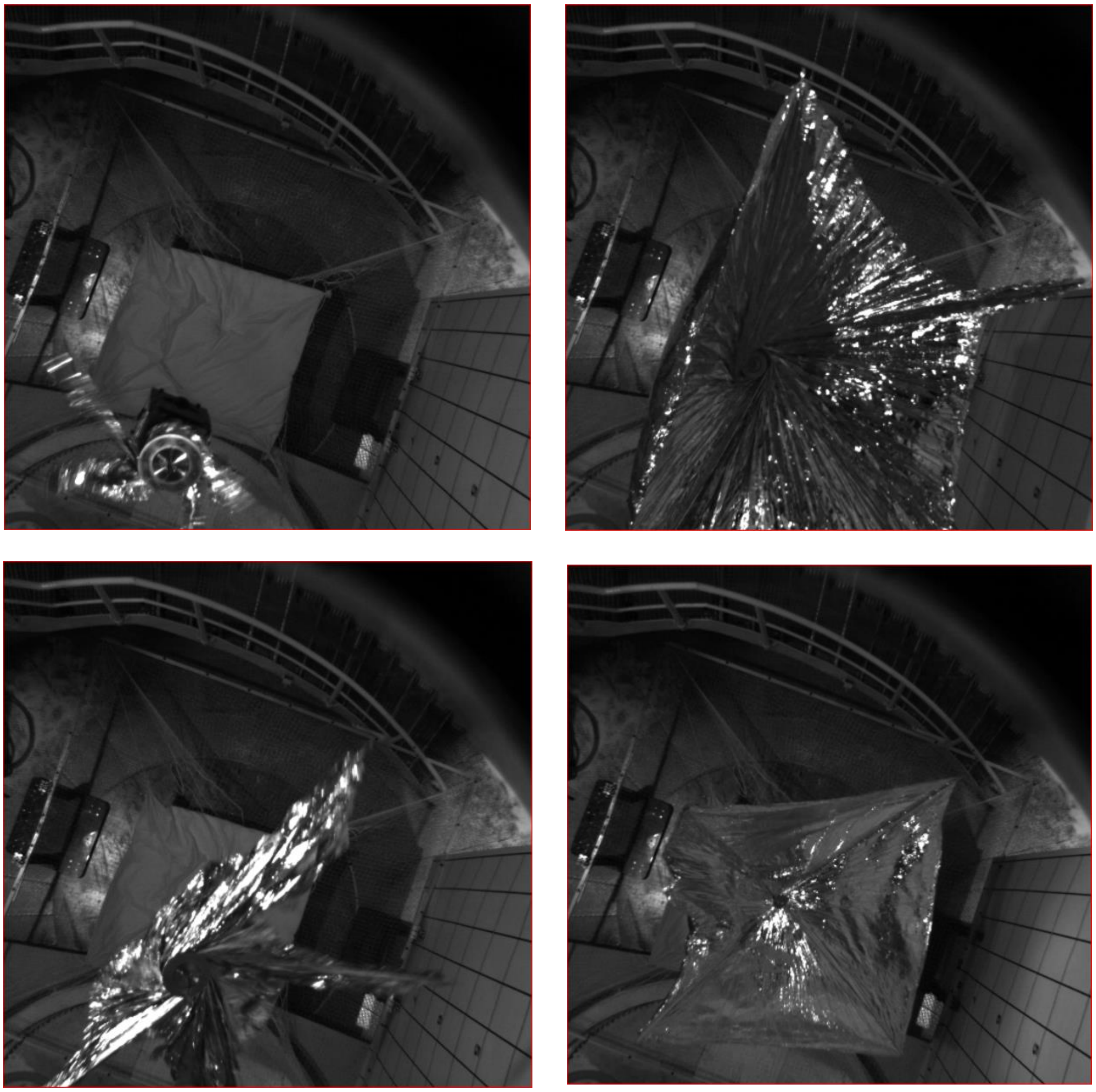

Figure 5-10 Images taken by the top camera during the first drop

The readings from the accelerometer mounted on the DM are shown on` the diagram below. Just before the drop the Z-axis (vertical) accelerometer shows a value of -1, after that the satellite is released and accelerations on all axes drop to 0. After counting down 430 ms the sail is released from the tray, ejected on the spring and unfolded. After nearly a second the satellite comes to a stall on the protective mesh (what illustrate the oscillations of accelerations in all 3 axes).

Data from accelerometer has being read with the frequency of 20 ms, which was 5 times slower that readings from cameras. For the next drop, the frequency of readings from accelerometer was reduced to 3 ms.

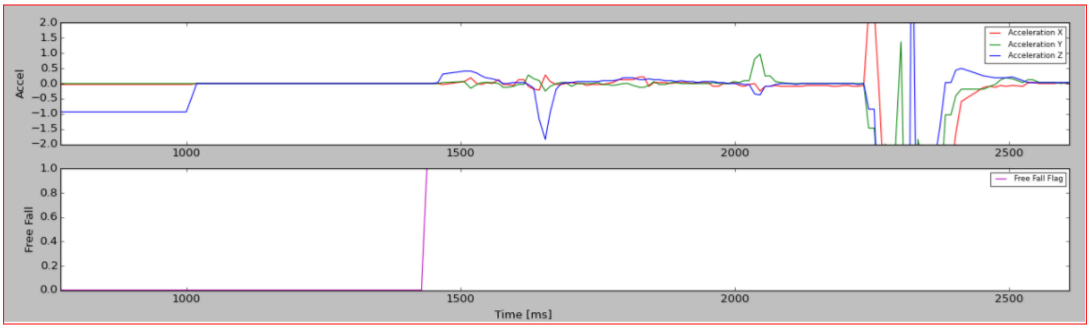

Figure 5-11 Accelerations of the DM sattelite in 3 dimensions detected by an on-board accelerometer during the first drop

5.4.1 SECOND DROP IN VACUUM

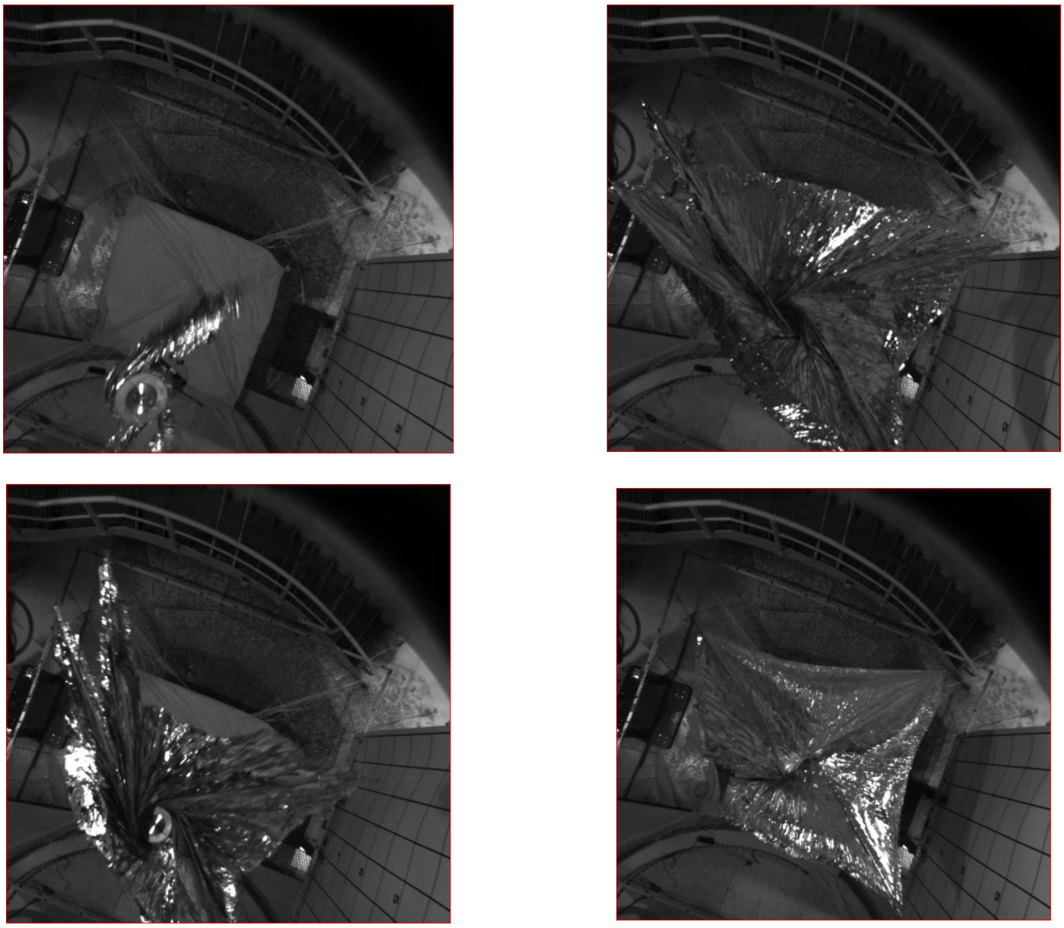

Figure 5-12 Theecond drop

Due to a technical challenge with the SD card, no records from accelerometer has been saved during the second drop.

5.4.2 THIRD DROP IN VACUUM

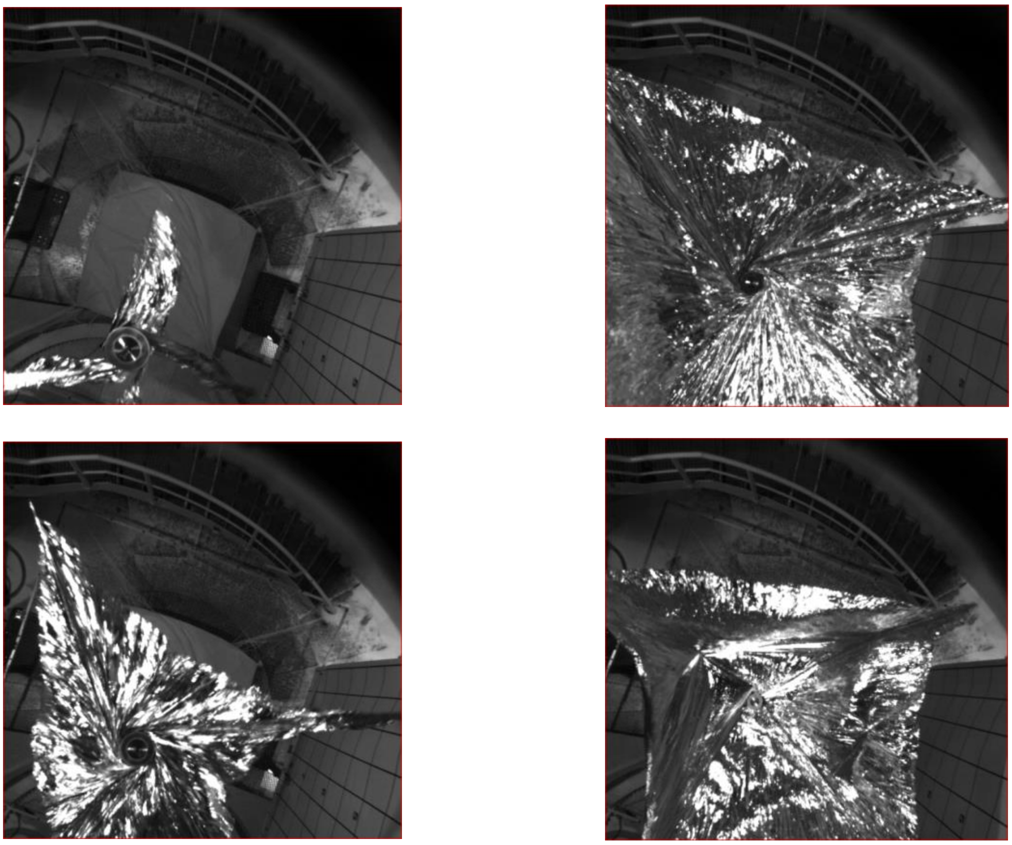

Figure 5-13 The third drop

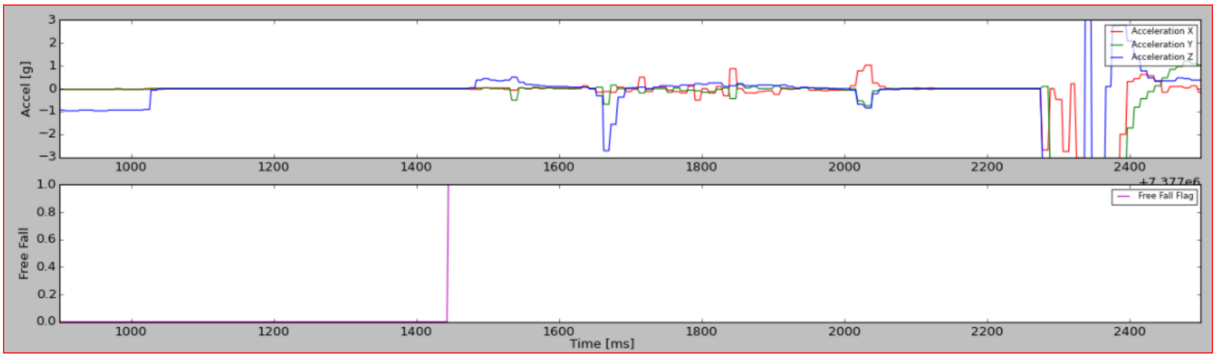

Figure 5-14 Accelerations of the DM during the third drop.

5.4.3 FOURTH DROP IN VACUUM

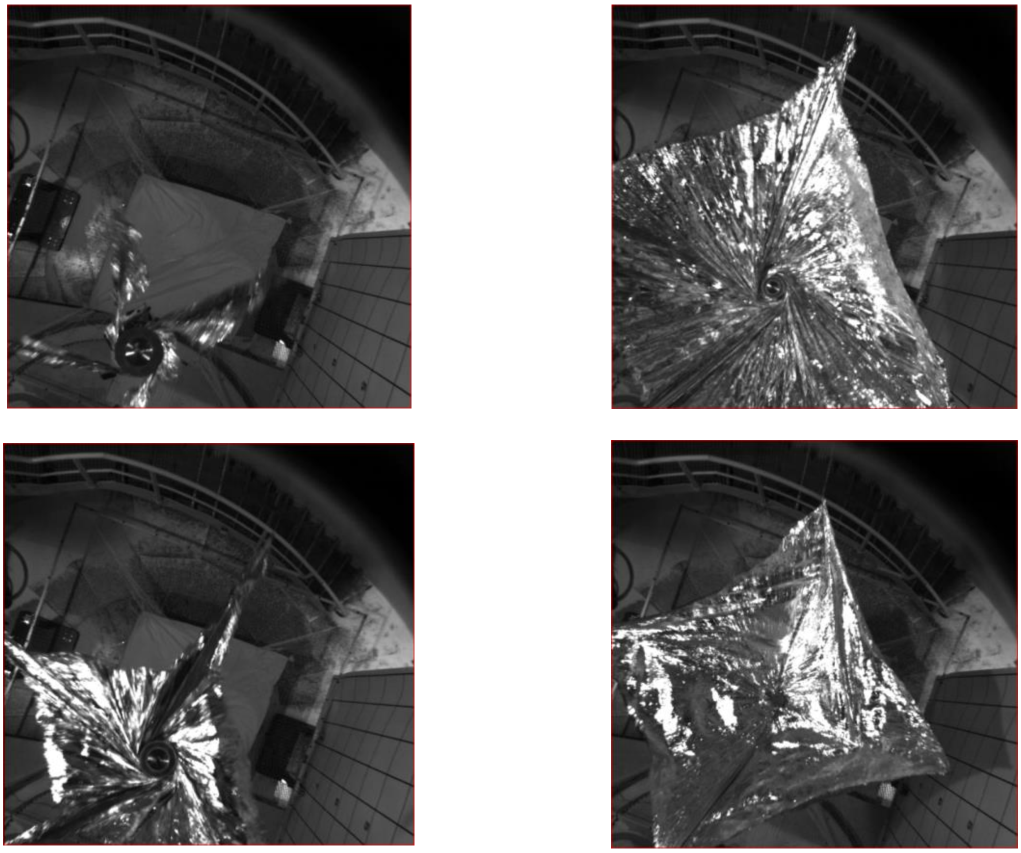

Figure 5-15 The fourth drop

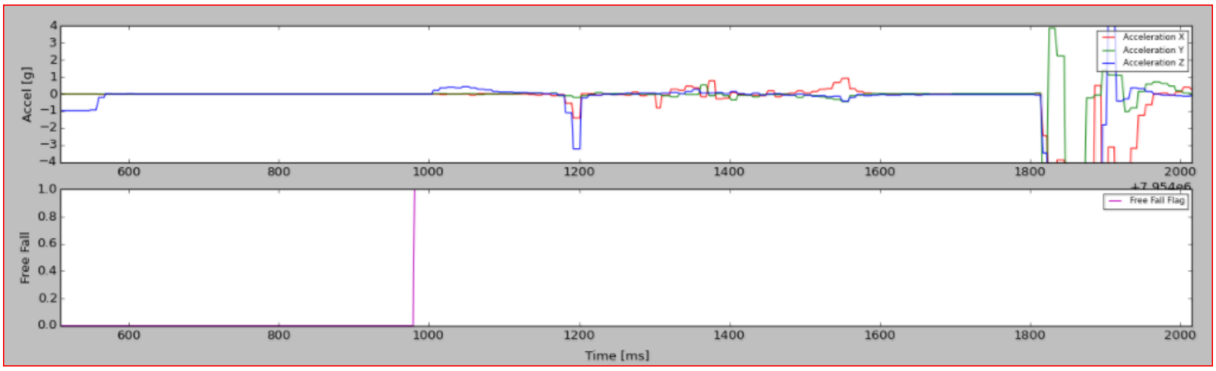

Figure 5-16 On-board accelerations during the fourth drop

5.5 SUMMARY AND FURTHER ACTIONS

The data gathered during the experiment is very valuable and will allow the students further analysis of the movement of the sail and it's effect on the CubeSat 2U type satellite in a given configuration. The students want to check if the current sail deployment system will be useful for a sail of bigger dimensions.

The experiment carried out in the Drop Tower has proved the effectiveness of the sail deployment system used in conditions which are close to those that are present on Low Earth Orbit. The next time the sail will be opened will be in orbit around Earth and this time the tests will focus on the impact of its area on the time of deorbit of the Cubesat 2U satellite.

The results of the experiment have been officially presented for the first time during the CubeSat Symposium 2017 (2nd December 2017) in Ostend, Belgium (*Deorbit Sail for the PW-Sat2 satellite mission – a low cost, low energy consumption and high efficiency system,* M. Gawin, D. Rafalo).

The PW-Sat2 team will also present its work based on the results of DropTES campaign on the International Conference on Aeronautical and Astronautical Engineering, New York, June 2018 and during Drop Tower Days at 42nd COSPAR Assembly in July 2018 in Pasedana, California.