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CRITICAL DESIGN REVIEW

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Abbreviated terms

ADCS	Attitude Determination and Control System
AP	Argument of Perigee
AR	Acceptance Review
CBK	Space Research Centre Polish Academy of Sciences
COMM	Communication subsystem
CONF	Configuration
DT	Deployment Team
EM	Engineering Model
EPS	Electrical Power System
ESA	European Space Agency
FM	Flight Model
FRR	Flight Readiness Review
GS	Ground Station
IADC	Inter-agency space debris coordination committee
ILOT	Polish Institute of Aviation
LEO	Low Earth Orbit
MA	Mission Analysis
MDR	Mission Definition Review
PDR	Preliminary Design Review
SC	Spacecraft
SKA	Studenckie Koło Astronautyczne (Students' Space Association)
SW	Software
TBC	To Be Continued
TBD	To Be Defined
TCS	Thermal Control System
WUT	Warsaw University of Technology

1 SCOPE

1.1 OBJECTIVE

This document contains the test plan for PW-Sat2 satellite hardware, including mechanical and environmental tests of integrated satellite and functional test of SADS and SAIL mechanisms. The main purpose of the satellite's test is to validate the design and prepare it to launch on board Falcon 9 rocket.

1.2 SCOPE

The PW-Sta2 satellite test models consists of:

- fully integrated PW-Sat2
- Structural-Thermal Model of PW-Sat2 (STM)
- miniSAIL model for functional test in TVAC chamber
- dummySAIL model for functional test in TVAC chamber

2 MODEL DESCRIPTION

2.1 SATELLITE

2.1.1 FULLY INTEGRATED SATELLITE

PW-Sat2 is a 2U (10x10x20 cm, 2.66 kg) CubeSat satellite with 2 main deployable subsystems: SAIL and SADS (described in sections 1.2 and 1.3). This document is focused on presenting the general concept of the tests' plan of the satellite as well as its crucial mechanisms and every requirement restricting the final design. More specific information is presented in documents: [PW-Sat2-C-05.00-DT-DR] and [PW-Sat2-C-10.00-CONF-CDR].

PW-Sat2's general design is presented in the Figure 1-1.

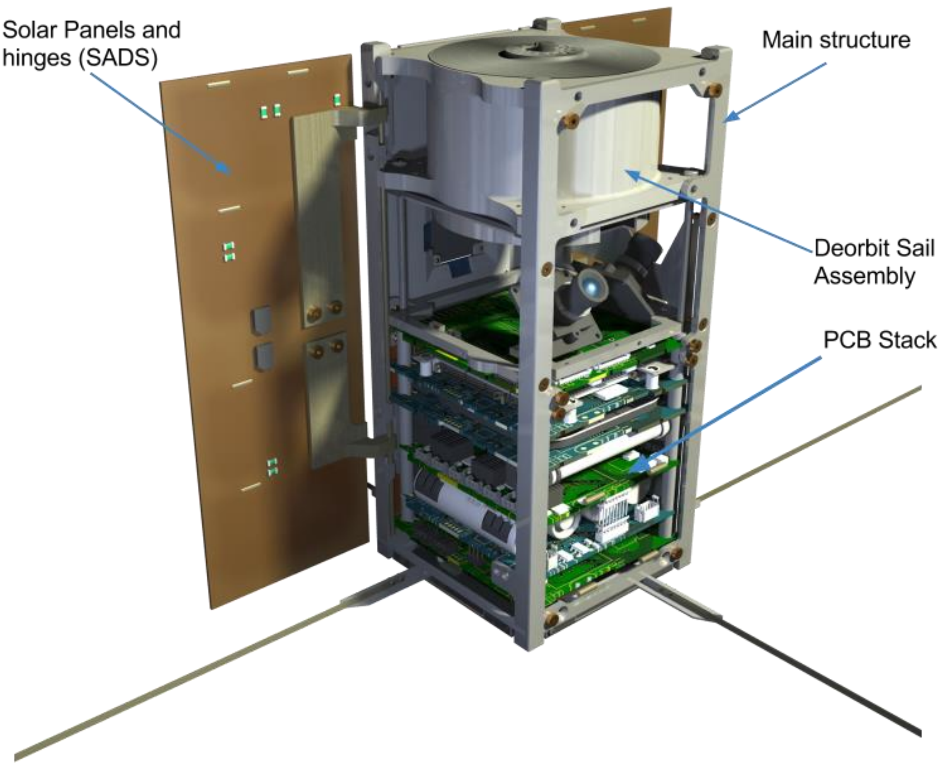

Figure 2-1 PW-Sat2 satellite's main subsystems configuration (outside walls and solar panels removed)

The satellite can be divided into several modules:

- Structure – two 2U X+, X- frames and Z- frame which is a base mount for PCB Stack
- SAIL – consists of: sail, sail's container and SRM (Sail Release Mechanism) located under the container (described in section 1.2)
- SS – Secondary Structure which serves both as an additional structural strengthening and cameras mount
- PCB Stack – consists of every piece of electronic equipment
- SADS and Solar Panels – one of the deployable mechanisms; Solar Arrays Deployable System consists of hinges on both Y sides of the satellite and Solar Panels connected to them (described in section 1.3)
- SARM – Solar Arrays Release Mechanism is not shown in the Figure 1-1; subsystem responsible for deploying the Solar Panels in the right time
- SunS – Sun Sensor is not shown in the Figure 1-1; one of the experiments of PW-Sat2 mission

From the satellite's testing point of view, except of the deployable mechanisms, PW-Sat2 Structure's strength is crucial to a successful mission. Structure, as it was assumed in the initial design, consists of 3 main frames. All structural elements are depicted on Figure 1-2. Primary structure is also an interface for many elements on the satellite, such as PCB stack, SARM, 1U Solar Panels, Sun Sensor, Sail's container and Secondary Structure. Structure positions them and is a stiff support for elements. Main structure is a mounting for kill switches and their rods as well.

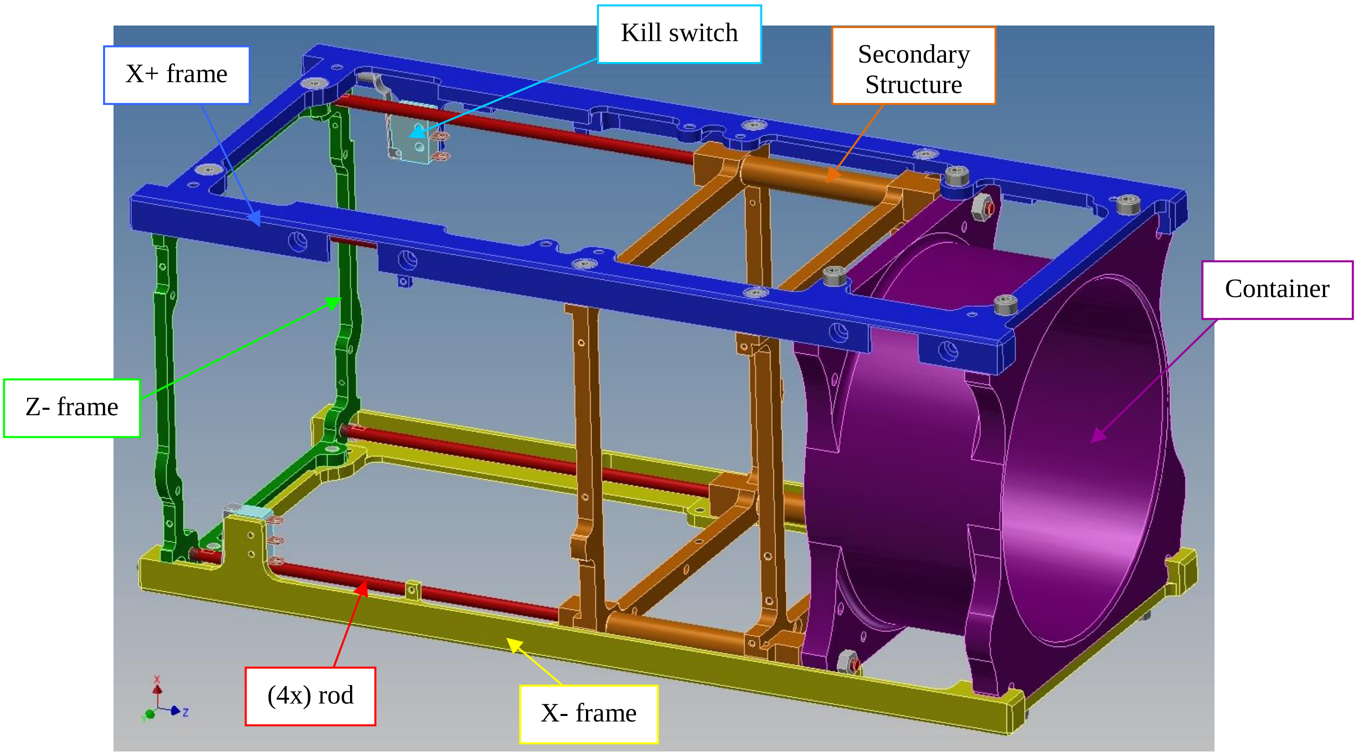

Figure 2-2 Assembly of entire structural elements

2.1.2 STRUCTURAL-THERMAL MODEL OF PW-SAT2 (STM)

STM Model will be prepared for preliminary test of PW-Sat2 components. From mechanical point of view will be identical to the Flight Model (FM) - main structure, mechanisms will be same as in FM. From thermal point of view STM model will be close to the FM - heaters will be mounted in hot points of the satellite to simulate real heat dissipation on the satellite. Electronics will be substituted by dummy electronics boards with exact mass equivalent (no electronics/software tests can be performed on STM Model). Deployable Solar Arrays will be replaced by its geometrical and mass equivalent.

2.2 SAIL

2.2.1 FULLY FUNCTIONAL SAIL MODEL

SAIL module is a first main deployable mechanism. Its whole subsystem consists of: sail's container, SRM (Sail Release Mechanism) and folded sail hidden in the container. SAIL module is presented in the Figure 1-3.

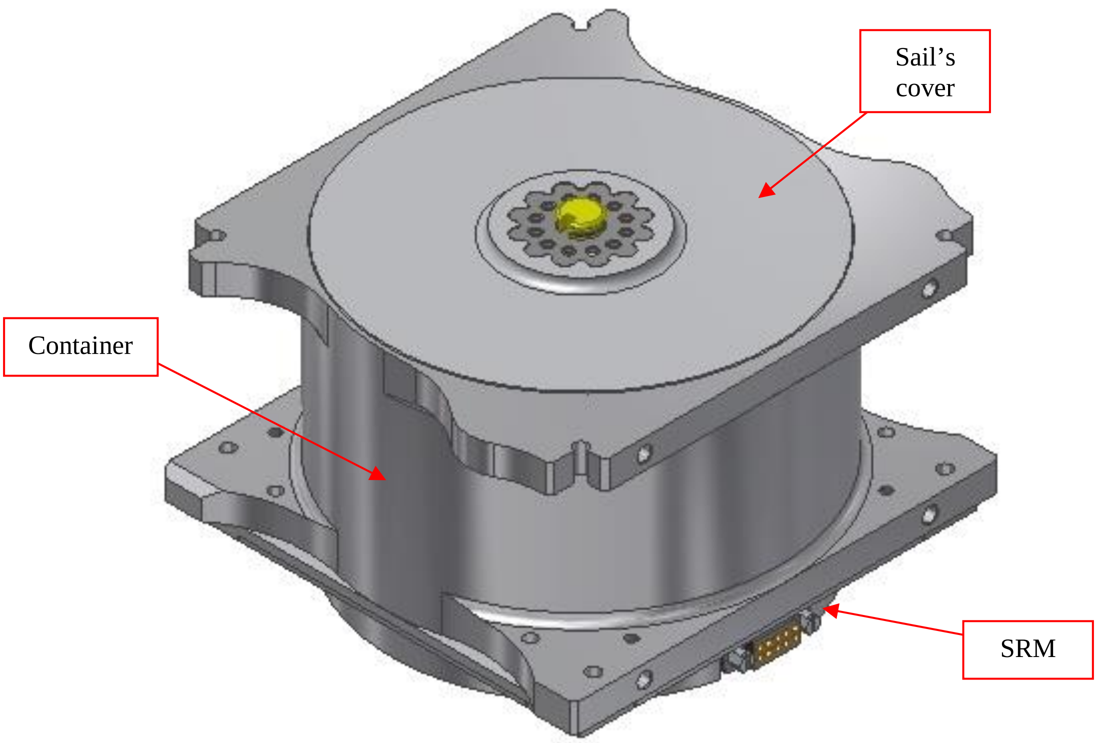

Figure 2-3 SAIL subsystem assembly

Despite the structural parts of the subsystem being made from aluminum what ensures that they are stable, the inside of the container is what requires testing the most. Sail is made from 4 steel tape springs which serve as the arms of the sail and square-shaped Mylar material stretched on the springs. After folding and mounting procedure the sail is hidden in the container just like in the Figure 1-4.

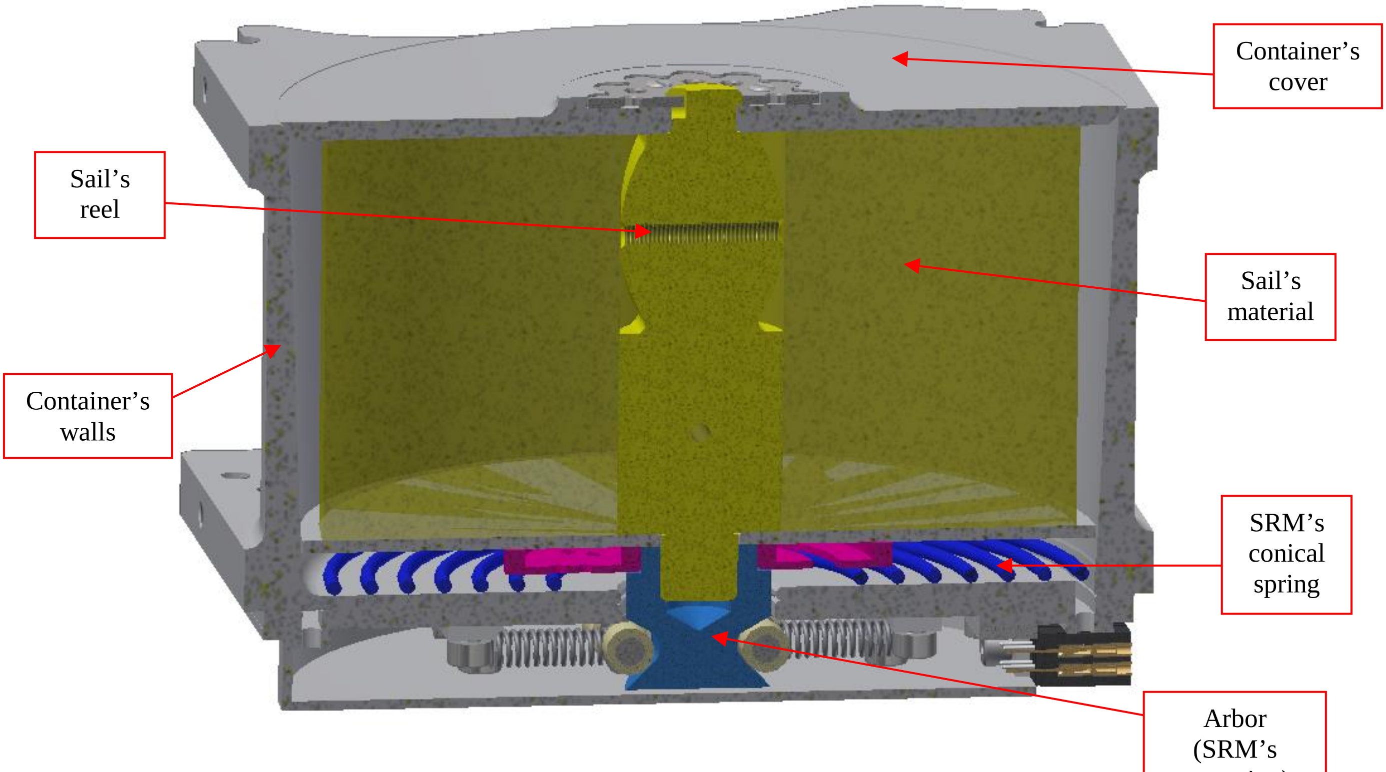

Figure 2-4 Section view of the inside of the container

Concluding just from the Figure 1-4, SAIL's module may be extremely fragile to any kind of vibration loads. Whole SRM-SAIL's reel interface consists of 2 SRM rods holding the sail's arbour (blue element connected to the reel) and a conical spring which is in constant stress during sail being folded and hidden into to container. Folded sail's material has a little amount of free space inside the container so its behaviour should also be tested.

2.2.2 MINISAIL MODEL FOR FUNCTIONAL TEST IN TVAC CHAMBER

Due to the large dimensions of the SAIL it is not possible to test its full-size version in TVAC Chamber. To solve this problem 2 smaller models of the SAIL will be prepared which will simulate unfolding of the SAIL (mini SAIL) and SAIL's deployment from the container (dummySAIL).

MiniSAIL is the smaller version of the SAIL, with the same construction but with only one ruler in each arm (to rescale opening torque of the arms in the small model). This miniSAIL model will be placed in TVAC chamber and deployed in vacuum conditions, in minimum temperature. Deploment mechanism will be based on the burnout of the Dyneema wire. On the Figure 2-5 miniSAIL construction and dimensions are shown.

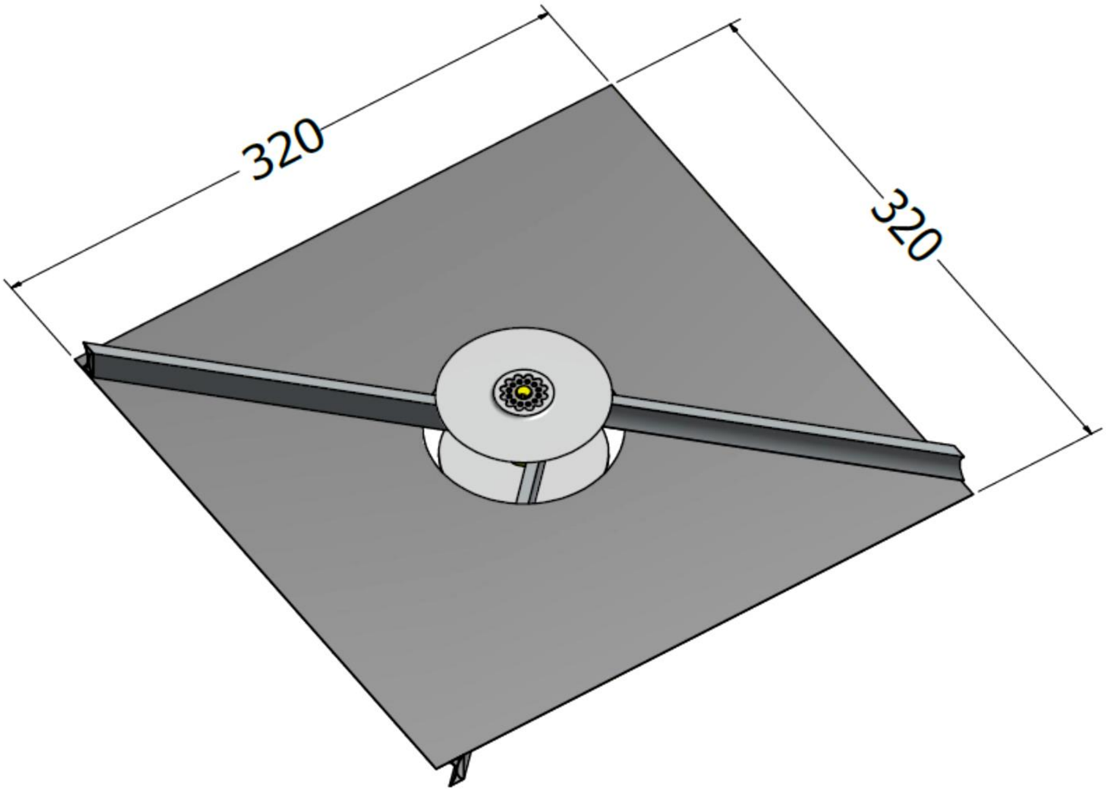

Figure 2-5 miniSAIL construction and dimensions (in mm)

2.2.3 DUMMYSAIL MODEL FOR FUNCTIONAL TEST IN TVAC CHAMBER

DummySAIL will be prepared to simulate real deployment of the SAIL from the container inside TVAC chamber. Model consists of full-size container and conical spring. SAIL is replaced by the cylinder with proper mass and size of the folded full-size SAIL. Only 100mm length arms will be mounted to the cylinder with Mylar foil - they will simulate pressure of the real SAIL's arms on the container wall.

Deployment of the dummySAIL will be based on the burnout of the Dyneema wire. On the Figure 2-6 dummySAIL construction and dimensions are shown.

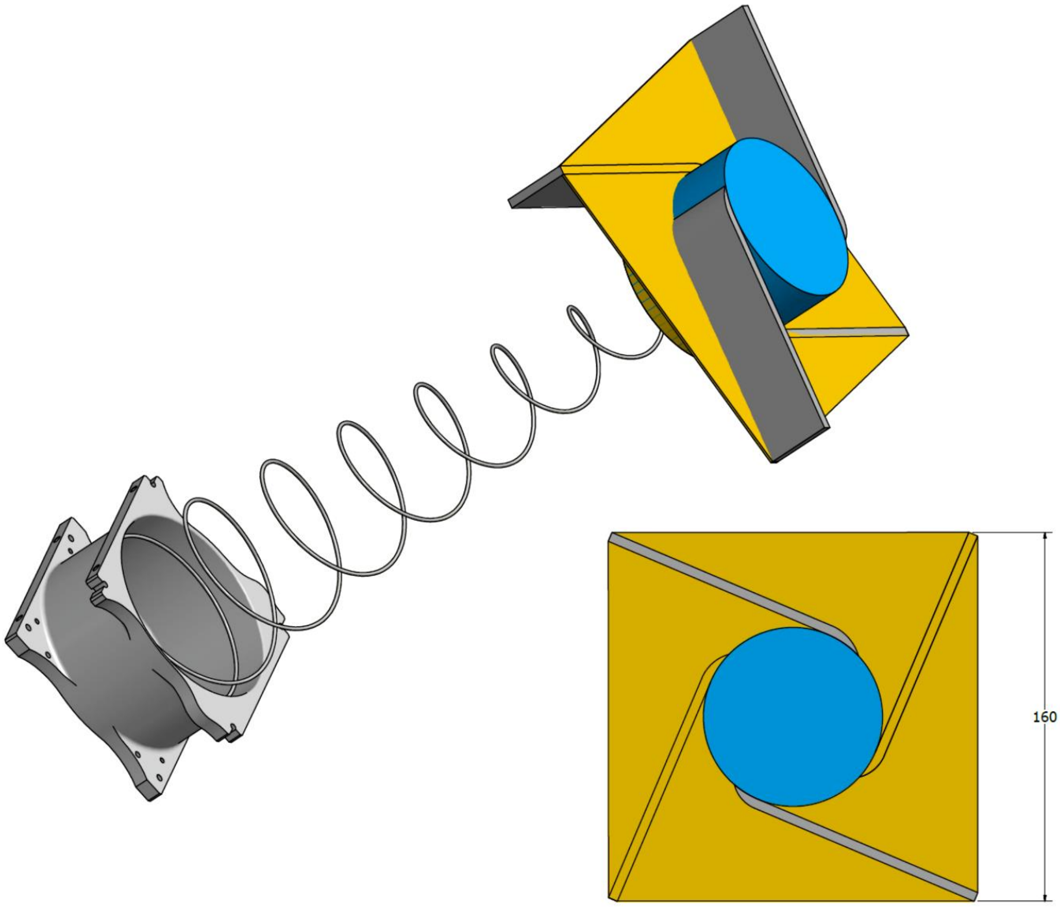

Figure 2-6 dummySAIL construction and dimensions

2.3 SADS

The second deployable mechanism is called SADS (Solar Arrays Deployable System). The final design consists of two hinges per side of the satellite (Y+ and Y-). Both pairs are placed on the X+ frame's rails. Each hinge consists of 2 pasted parts mounted to the Structure, a shaft, 2 springs fixed on the shaft, 4 washers and a sleeve. Hinges design is presented in the Figure 1-5.

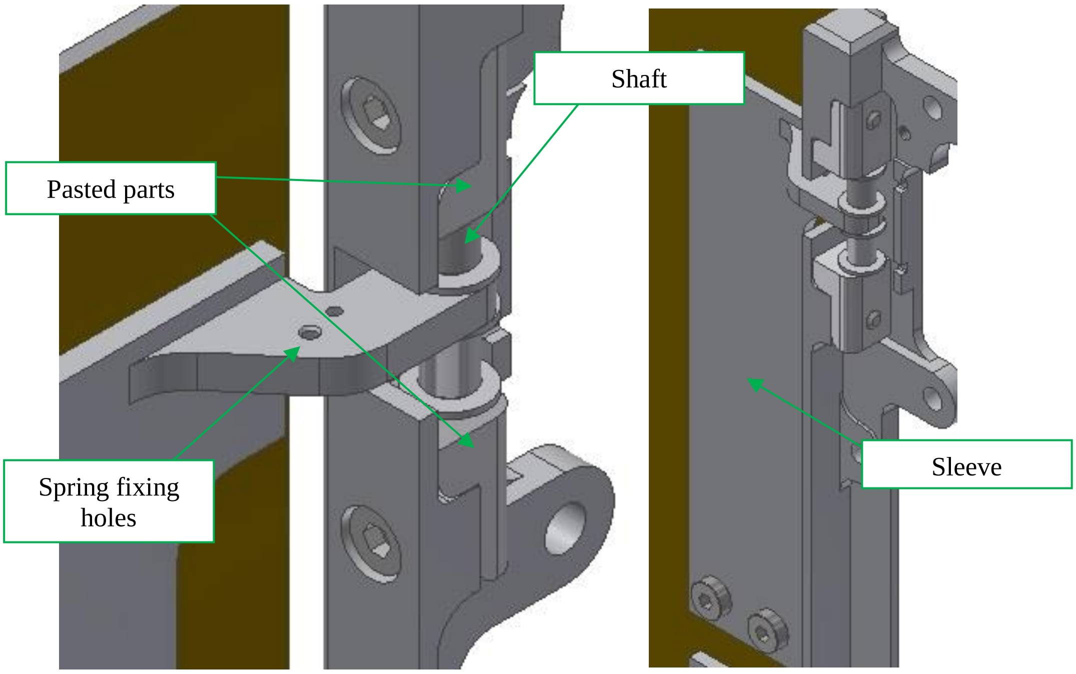

Figure 2-7 Hinges design.

Hinges are the interface between the Structure (X+ frame) and 2U Solar Panels. The only free space on the Panel, where holes for screws can be done, is in the middle of it. Because of that, the Solar Panel is connected with sleeves both by screws and glue. Two screws M3 for each sleeve are located in the middle of the Panel. The whole sleeves' surface is glued to the inner Solar Panel surface. The connection is presented in the Figure 1-6.

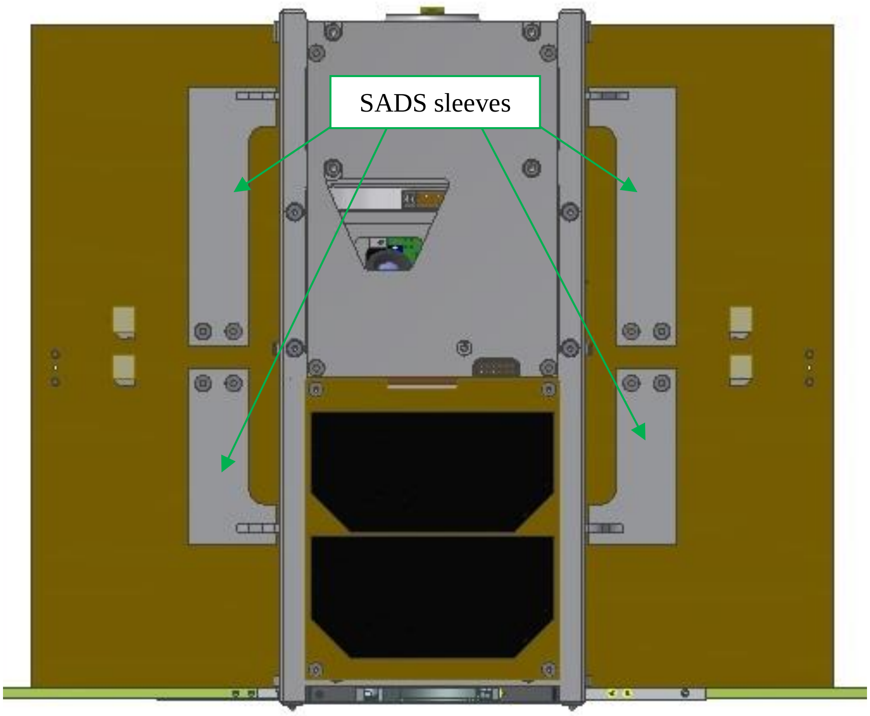

Figure 2-8 Hinges-Solar Panels interface.

From the SADS testing point of view, hinges can be very fragile to the vibration loads. They are made from very tiny elements and yet they should stabilize the 2 2U, 90 g each Solar Panels. Additionally, the weak spot which requires testing is the glue/screws connection between the sleeves and Solar Panels.

3 Environment

3.1 Vibration

According to the CubeSat Design Specification, PW-Sat2 structure has to fulfil many requirements, namely: satellite and rails dimensions, radius and roughness of rails, materials and others.

As PW-Sat2 is launched on Falcon 9 rocket, it has to withstand loads occurring during ascent and separation events. SpaceX, producer of the rocket, provides loads only on the main interface, where the primary payload is attached. CubeSats are deposited in so called QuadPack (CDS names it P-POD), which position in payload's assembly is not precisely defined. Because of that launch provider, ISIS, recalculated this loads and provided them as a loads defined on the QuadPack's rails. These values are presented in current chapter.

3.1.1 Quasi-static

Structure and whole satellite have to withstand 18,75 g acceleration in every axis. Table 2-1 shows load during particular tests. Structure will be designed to hold out this acceleration occurring in all three axes at the same time, but test will be performed on one axis at a time.

Table 3-1 Quasi-static loads during tests

Characteristic		Qualification	Acceptance	Proto-flight
Test		Required	Not required	Required
Directions	{BRF}	X, Y, Z		X, Y, Z
Acceleration	{LRF}	+ 18.75 [g]		+ 18.75 [g]
Duration	Centrifuge	60 [sec]		30 [sec]
	Sine burst	≥ 5 [cycles @ full level]		≥ 5 [cycles @ full level]

3.1.2 Natural frequencies

According to the launch provider, fundamental frequency has to be higher than 90 Hz. Resonance survey test will be performed with sinus amplitude 0,4 g. Detailed specification of test is shown on Table 2-2.

Table 3-2 Resonance survey test specfcation

Characteristic		Qualification	Acceptance	Proto-flight
Test		Required	Required	Required
Directions	{BRF}	X, Y, Z	X, Y, Z	X, Y, Z
Type		Harmonic	Harmonic	Harmonic
Amplitude	See Notes, 2	0.4 [g]	0.4 [g]	0.4 [g]
Frequency range		5 – 2000 [Hz]	5 – 2000 [Hz]	5 – 2000 [Hz]
Sweep Rate		2 [oct/min]	2 [oct/min]	2 [oct/min]

3.1.3 RANDOM VIBRATIONS

Structure has to withstand random vibration levels described on Table 2-3 and Figure 2-4. All levels are assumed for each axis are the same. Structure is designed to survive most severe loads, namely qualification levels. Total RMS in random vibrations is 14,1 g.

Table 3-3 Random vibriations test specification

Characteristic		Qualification	Acceptance	Proto-flight
Test		Required	Required	Required
Directions	{BRF}	X, Y, Z	X, Y, Z	X, Y, Z
Profile	Frequency range [Hz]	Amplitude [g^2/Hz]	Amplitude [g^2/Hz]	Amplitude [g^2/Hz]
	20	0.026	0.013	0.026
	50	0.16	0.08	0.16
	800	0.16	0.08	0.16
	2000	0.026	0.013	0.026
RMS acceleration		14.1 [g]	10.0 [g]	14.1 [g]
Duration		180 [sec/axis]	60 [sec/axis]	60 [sec/axis]

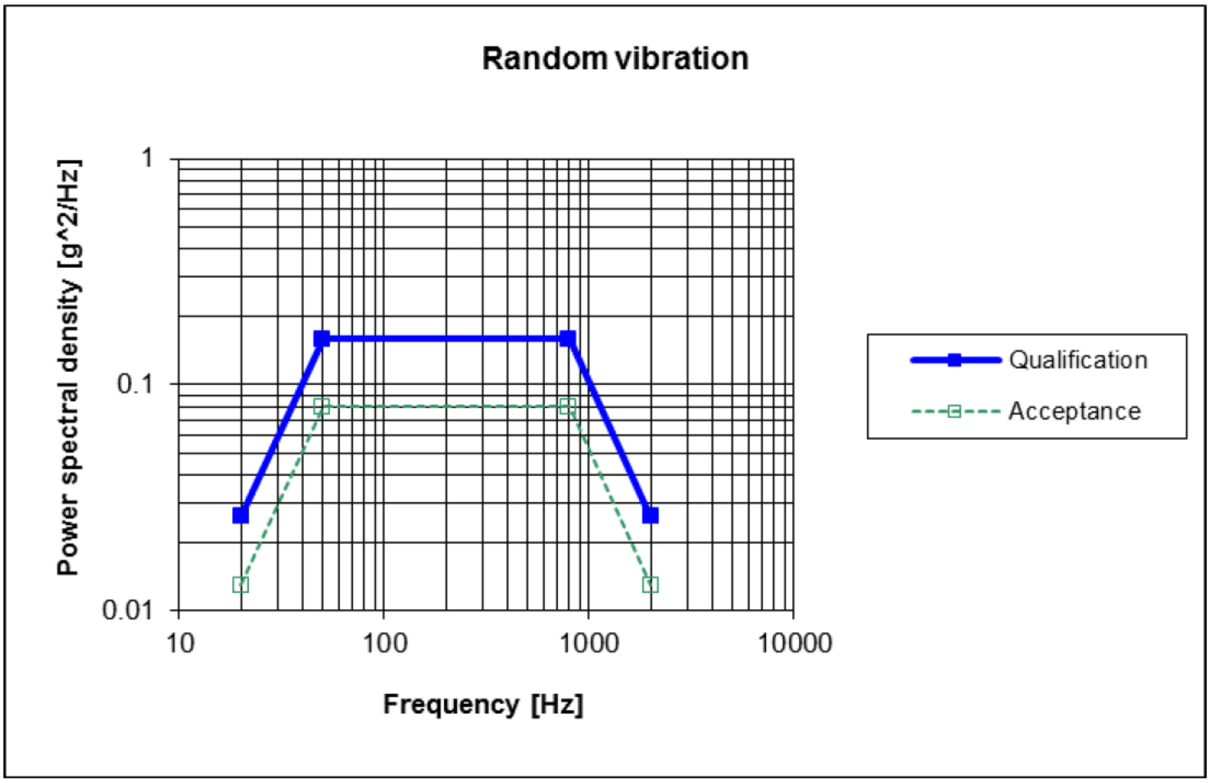

Figure 3-1 Random vibriations test specification

3.1.4 SHOCKS

Levels of shocks are depicted on Table 2-4, and they profile on Figure 2-5. Again loads are applicable for all three axes. It is possible, that FM will not need shock tests, provided sufficient FEM analysis. There is also considered carrying out shock test on the engineering model of the structure.

Table 3-4 Shocks test specification

Characteristic		Qualification	Acceptance	Proto-flight
Test		Not required	Analysis required	Analysis required
Directions	{BRF}		X, Y, Z	X, Y, Z
Profile	Frequency [Hz]		Amplitude [g]	Amplitude [g]
	20		30	30
	2000		1000	1000
	10000		1000	1000
# of shocks			- [/axis]	- [/axis]

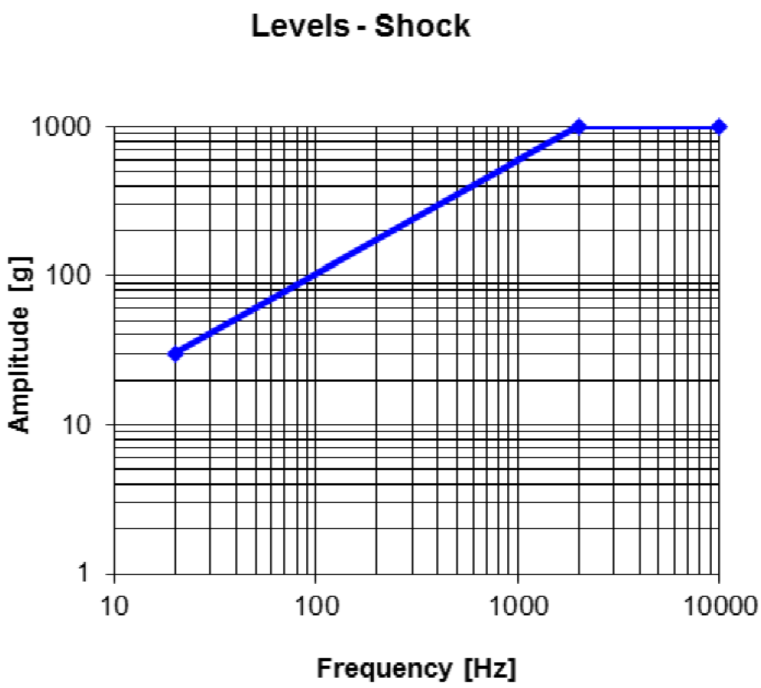

Figure 3-2 Shocks test specification

3.2 TEMPERATURE

[PW-Sat2-C-09.00-TCS-CDR] document presents the precise requirements of every component located in the satellite. Due to the high variations in temperature on the structure across the whole orbit, a solar panel deployment test under thermal stress needs to be performed to verify the performance of the release mechanism.

According to the results presented in [PW-Sat2-C-09.00-TCS-CDR] document, the minimum temperature, that was estimated for solar panels is -70°C and -4°C for structure to which the hinges are attached to. Therefore, the hinges deployment needs to be tested at -70°C (-2°C for acceptance level) for the whole mechanism and the SAIL deployment mechanism at -4°C (-10°C for acceptance level).

4 TEST PHILOSOPHY

It is impossible to perform deployment test of the full-size SAIL after integration to the satellite and also in the TVAC chamber. MiniSAIL and dummySAIL models are performed to investigate if SAIL can be succesfully deployed in the vacuum conditions, in minimum temperature.

To perform full-size SAIL deployment test 5 models of the SAIL will be build, all according to the same procedure, by the same group of people. 4 of this models will be deployed and one will be destinated to the Flight Model of the satellite (this FM of the SAIL will not be deployed due to the Mylar foil wearing during multiple folding and unfolding: successful deployment of the 4 other SAILs will gave certainty level of 80% that deployment of the SAIL will be successful on orbit).

Due to the problems of SAIL testing the test campaign is devided into 2 paths:

- 1st - for the whole, integrated satellite (with folded SAIL inside the container)
- 2nd - SAIL test campaign

4.1 SATELLITE TEST PLAN

The whole satellite will undergo vibration and TVAC tests, with functional test of Solar Arrays Deployment System (SADS) before and after each test. On the Figure 4-1 test plan for the integrated satellite is shown. It consists of vibration and TVAC test - before each of this test the deployment of the SADS mechanism will be made. Functional test I is the reference test for the deployment after vibrations (Functional test II) and TVAC (Functional Test III).

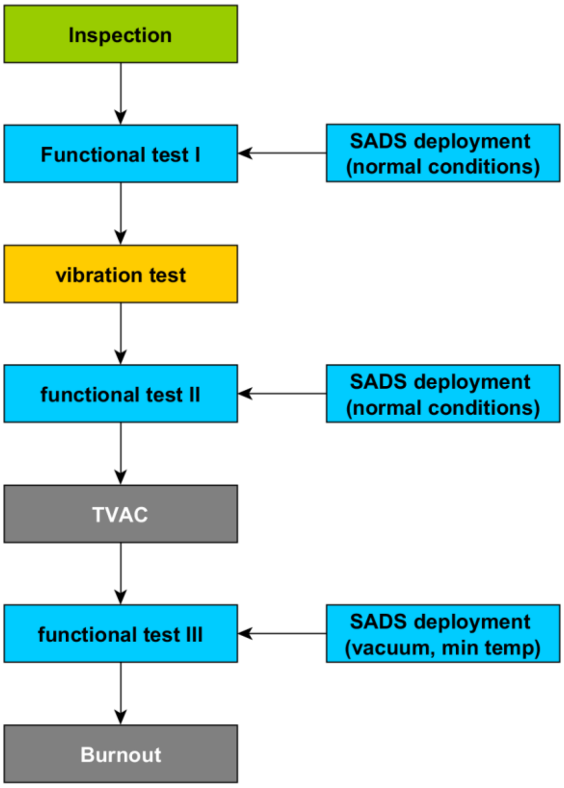

Figure 4-1 PW-Sat2 satellite environmental and mechanism functional testing

4.2 SAIL TEST PLAN

In the test plan of the SAIL 6 models of the SAIL will be used: 4 full-size, qualification models identical to the FM and 2 smaller models for TVAC testing. On the Figure 4-2 Test Campaign for the SAIL is shown - it includes testing of the qualification models on vibration levels and miniSAIL and dummySAIL tests in vacuum environment, in minimum temperature.

Functional test between vibration and TVAC consists of 4 deployments of full-size SAILs and 6 reference deployments of the small SAILs (3 x miniSAIL and 3x dummySAIL).

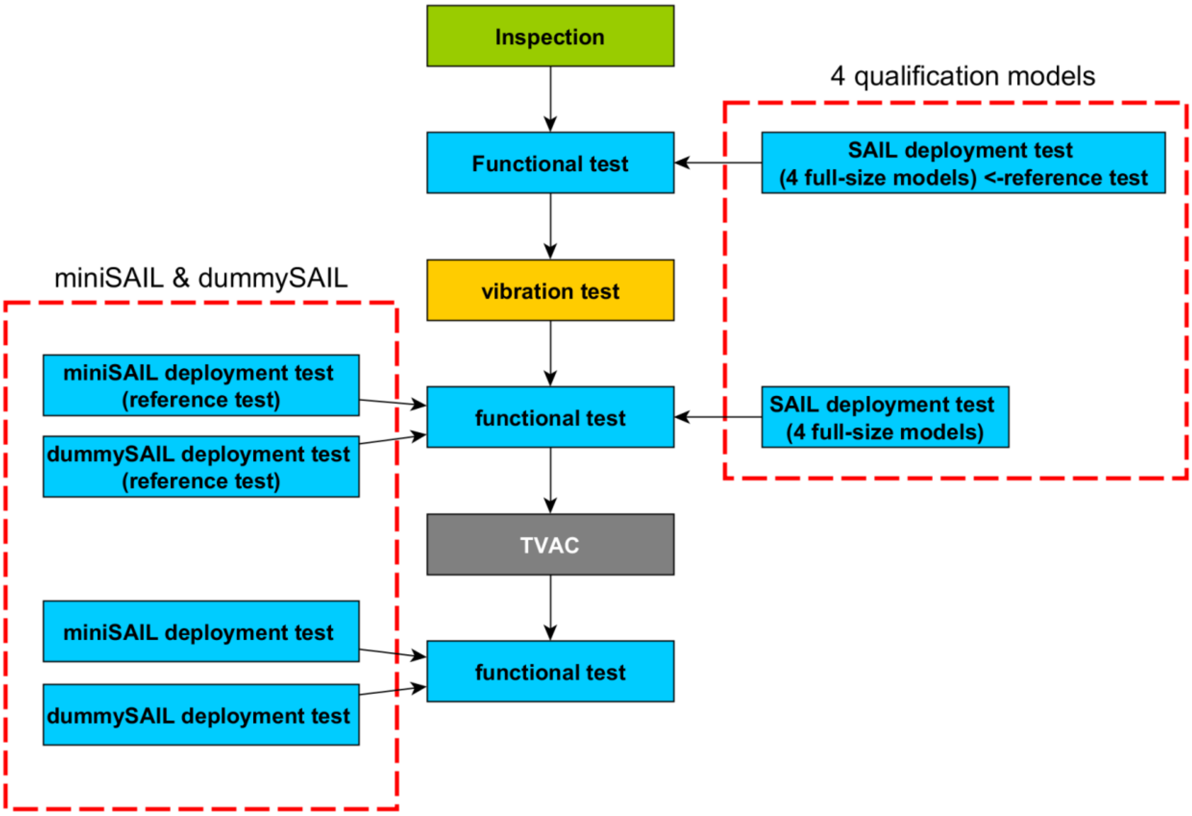

Figure 4-2 SAIL Test campaign

5 FUNCTIONAL TESTS

5.1 NORMAL CONDITIONS

Test in normal conditions (room temperature, standard pressure) is prepared before and after deployment test of SADS and SAIL's models. It will show if the operation of mechanisms is correct

5.1.1 SADS

Solar Arrays Deployment System functional test will give a knowledge about correctness of the mechanism deployment and will show the behavior of SADS mechanism and its surrounding systems.

The deployment of the mechanism is be based on burnout of the Dyneema wire. Entire process should be performed in Clean Room ISO8, in normal gravity environment.

The satellite assembly shall be placed in vertical position meaning the Sail Subsystem shall be faced up. To provide correct and firm position of satellite during entire test process there is a need of specific MGSE, that keeps satellite in the required position. EGSE which will control the burnout process will be required.

There is no need to lower Panel's mass impact when deploying, because of small dimensions and low mass of Solar Panels. When assembly of the mechanism is prepared and firmly located in the MGSE, EGSE will send a signal to burn the Dyneema wire which causes mechanism deployment. Entire test will be observed and recorded with High Speed Camera, to enable precise and detailed analysis of the Panels' movement. Test will be qualified as satisfactory if the deployment is smooth, without disturbances, and after deployment Solar Panels are in fully opened position.

5.1.2 SAIL

SAIL is the main payload onboard PW-Sat2 satellite and it is crucial to ensure the proper SAIL System reliability. To achieve good reliability a series of tests has been performed on SAIL prototypes and are also planned for the near future. The most important and the most difficult part of test campaign is to perform the entire deployment process in the environment similar to the space environment.

A lot of SAIL prototype deployments has been done, to develop the SAIL design and to improve it's producing and testing procedures. Mechanism design is now refined which guarantees correct deployment, when entire producing, folding and assembling process is done in accordance with appropriate procedure.

Because of SAIL surface (Mylar foil) can be damaged during multiple foldings and unfoldings it was decided not to test the Flight Model of the SAIL – instead 5 identical models of the SAIL will be produced, in absolute accordance with producing, folding and assembling procedures. Four of them (random chosen) will be deployed in microgravity environment. The microgravity environment for Sail deployment will be provided by preparing ground with coefficient of friction as low as possible. Successful deployment of all 4 SAIL models will give us reliability of 80%.

Deployment will be based on the burnout of the Dyneema wire. Assembled SAIL should be placed in he Container and armed by Sail Release Mechanism. This assembly must be placed 150 mm under prepared ground and connected to the EGSE which control the burnout of Dyneema wire

The test will be qualified as fully successful when SAIL deployment process will be correct in every aspect:

- Every flat spring in the SAIL's arm is fully deployed and straight
- Entire Sail surface is exposed
- There were no problems and alarming delays during Dyneema burnout and during Sail Surface deployment

5.2 Functional test in TVAC

Tests in TVAC chamber consist of SADS, miniSAIL and dummy SAIL deployment in high vacuum conditions in minimum temperature. This tests will give us information about mechanisms working in on-orbit conditions and give us confidence that they will successfully deploy on-board PW-Sat2. Thermal cycles specification is TBD

5.2.1 SADS

The aim of the test is to simulate the deployment of the SADS in minimum temperature and vacuum conditions. Deployment mechanism will be based on the burnout of the Dyneema wire. After the Dyneema wire is burnt the torsion springs placed inside the hinges will open the Solar Arrays. The success of the test will be confirmed if Solar Arrays will be opened to 90˚ without any visible damage.

To perform this test it is necessary to use fully integrated satellite. MGSE and EGSE for TVAC test will be necessary.

Mounting to the TVAC chamber will be obtained by MGSE which holds integrated satellite in place, in the vertical position (Z-axis perpendicular to the TVAC table). Test will be monitored using high speed camera, through the window in TVAC chamber.

5.2.2 MiniSAIL

The aim of the test is to simulate the unfolding of the SAIL material in minimum temperature and vacuum conditions. Deployment mechanism will be based on the burnout of the Dyneema wire. After the Dyneema wire is burnt the MiniSAIL arms will start to unfold from the reel in lateral plane. Material will be deployed and spread by flat steel tapes used as SAIL arms. The success of the test will be confirmed if the SAIL will be fully opened without any visible damage.

MGSE and EGSE for TVAC test will be necessary.

MGSE will consist of anodized aluminum plate used to connect the sail's reel to the chamber's table. The plate will be used instead of bottom cover in SAIL assembly and will be fixed to the chamber's table. Reel with folded sail, arbor and top cover will be able to rotate freely during the unfolding stage after deployment. TBD screws will be used to screw the bottom plate to the chamber's table. MGSE design is presented on the figure below.

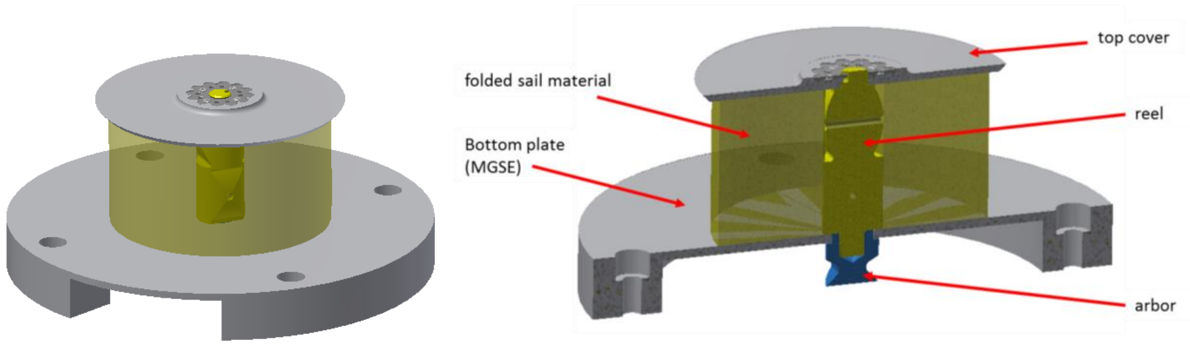

Figure 5-1 MGSE for miniSAIL TVAC test

EGSE will consist of the thermal knife system used to burn Dyneema wire wrapped around the folded SAIL material. The board with thermal knife system will be inside the TVAC

Thermal sensors will be glued to the bottom side of bottom plate and to the top side of the top plate (TBC).

Test will be monitored using high speed camera, through the window in TVAC chamber.

5.2.3 DUMMYSAIL

The aim of the test is to simulate real deployment of the SAIL from the container inside TVAC chamber. Deployment mechanism will be based on the burnout of the Dyneema wire. After the Dyneema wire is burnt the DummySAIL will be pushed out of the container by the conical spring. After leaving the container material will be deployed and spread by flat steel tapes used as SAIL arms. The success of the test will be confirmed if the SAIL will deploy from the container being fully opened without any visible damage.

MGSE and EGSE for TVAC test will be necessary.

MGSE will consist of anodized aluminum plate used to connect the sail's container to the chamber's table. The plate will hold the container in horizontal, fixed position with regard to the chamber's table. Reel will be replaced with the cylinder of bigger diameter, but same height and interfaces in order to achieve similar force and friction of the DummySAIL arms on the container's inside wall. Deployment will be performed by SRSM placed under the container as in flight model of Deorbit Sail. Thermal knife system will be placed on additional board inside the chamber. After the Dyneema wire is burnt DummySAIL will be pushed out of the container by conical spring with its damping system. TBD screws will be used to screw the bottom plate to the chamber's table. MGSE design is presented on the figure below.

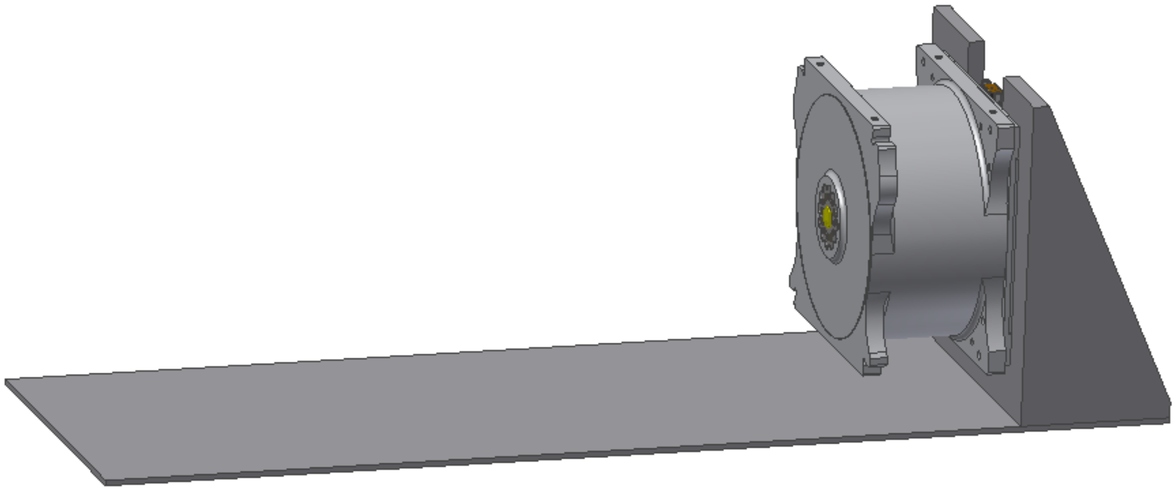

Figure 5-1 MGSE for miniSAIL TVAC test

EGSE will consist of the thermal knife system used to burn Dyneema wire wrapped around the folded SAIL material. The board with thermal knife system will be inside the TVAC

Thermal sensors will be glued to the MGSE aluminum plate holding the container and on SRSM cover (TBC).

Test will be monitored using high speed camera, through the window in TVAC chamber.

6 FACILITIES

6.1 TVAC CHAMBER

The main facility to perform TV test is Thermal Vacuum Chamber, available in Space Research Centre Polish Academy of Sciences (CBK PAN).

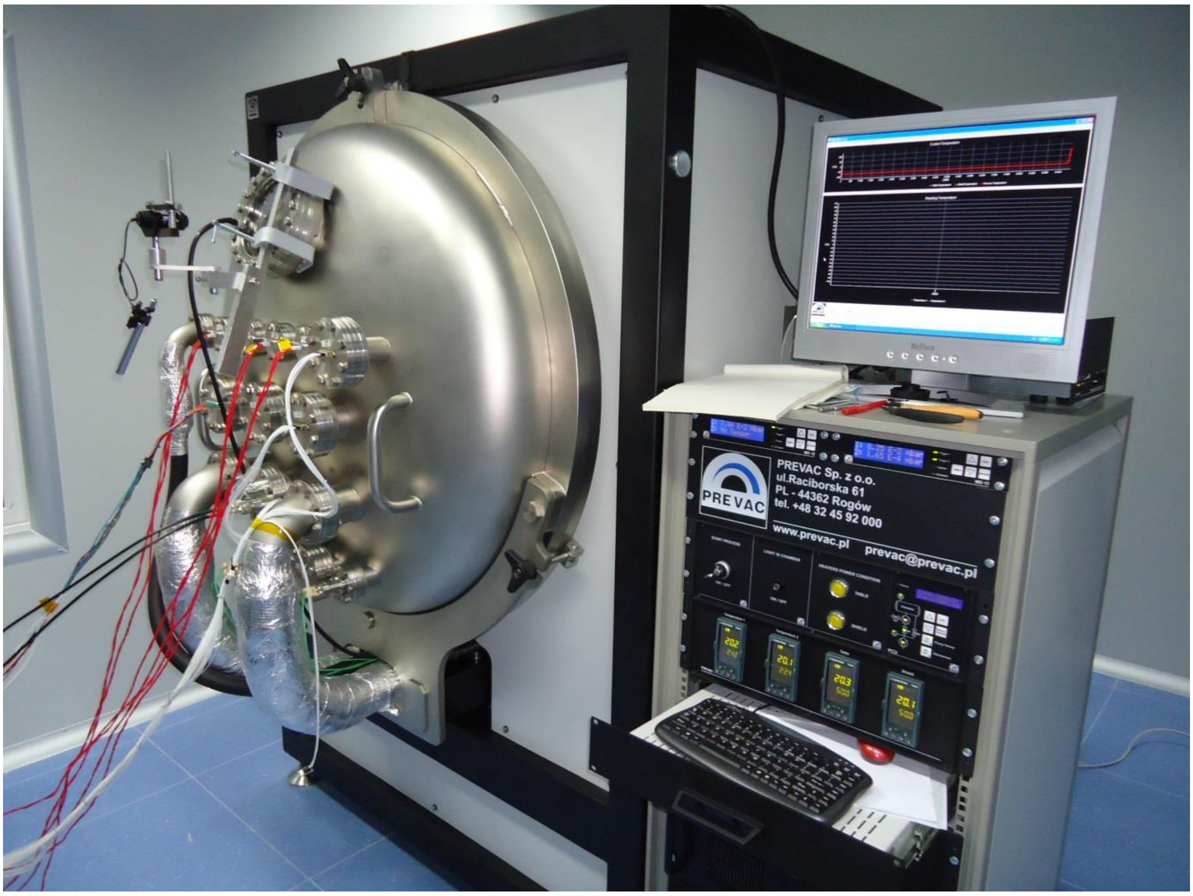

Figure 6-1 TVC in CBK cleanroom

TVC chamber is located in ISO7 cleanroom lab.

Cleanliness of the area is controlled periodically and on-demand. Background cleanliness was tested. Temperature is continuously monitored and controlled. Set up at 22°C ± 1°C. Relative humidity is monitored but not controlled in the cleanroom.

Thermal Vacuum Chamber specification is shown in the table below:

Table 6-1 TVC parameters

Parameter	value
Table size	1050 x 570 mm
Maximum height of test unit	470 mm
Temperature range	-80°C, +90°C
Maximum gradient	2°C (up) and 1°C (down)
Vacuum system	oil free, turbomolecular pump
Vacuum range	below 10^{-6} mbar at room temp
Cooling	LN2
ESD safe	yes
Mass spectrometer	yes (RGA 300)

Table 6-2 TVAC main parameters

Inside the chamber instruments can be mounted to the table using M5 screws. The chamber has also a shroud with controlled temperature. Main dimensions of the chamber are shown on the figures below.

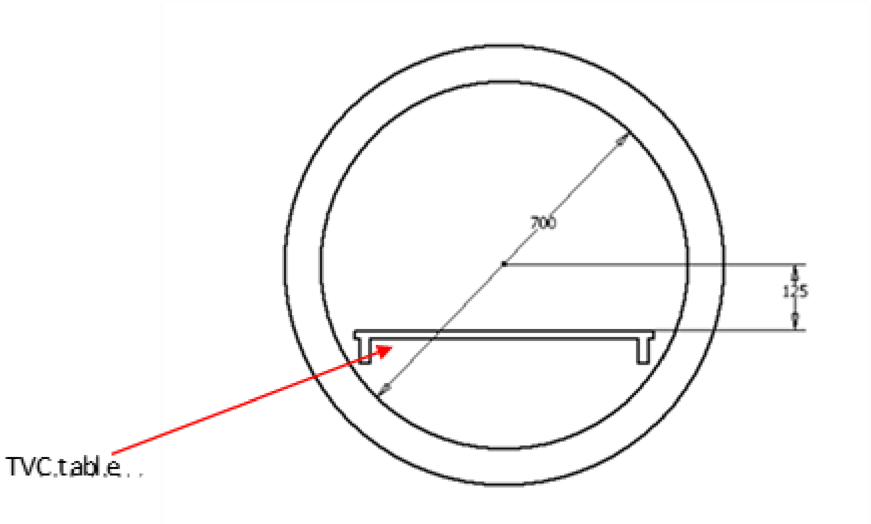

Figure 6-2 TVC main dimensions (shroud diameter ~700mm)

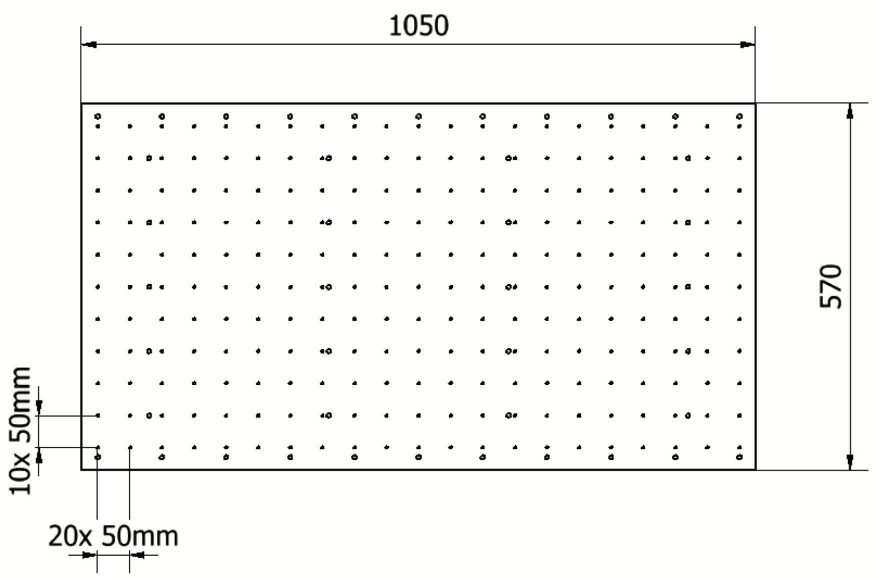

Figure 6-3TVAC table

6.2 SHAKER SYSTEM

For the vibration test the shaker system from Polish Institute of Aviation (ILOT) will be used. Shaker system has a slip table and also head expander. It is possible to use cleanroom chamber (which is located in the same room as the shaker) for satellite inspections, Accelerometers mounting etc. Shaker properties are shown in the table below:

Table 6-3 ILOT shaker properties

Properties	**value**
Frequency range	5-2500Hz
Max acceleration (sine)	900m/s
Max acceleration (random)	640 m/s
Max acceleration (shock)	1828m/s
Max weight of the instrument	400kg
Slip table dimensions	750x750mm
Head expander dimension	Diameter 610mm

Figure 6-4 ILOT shaker

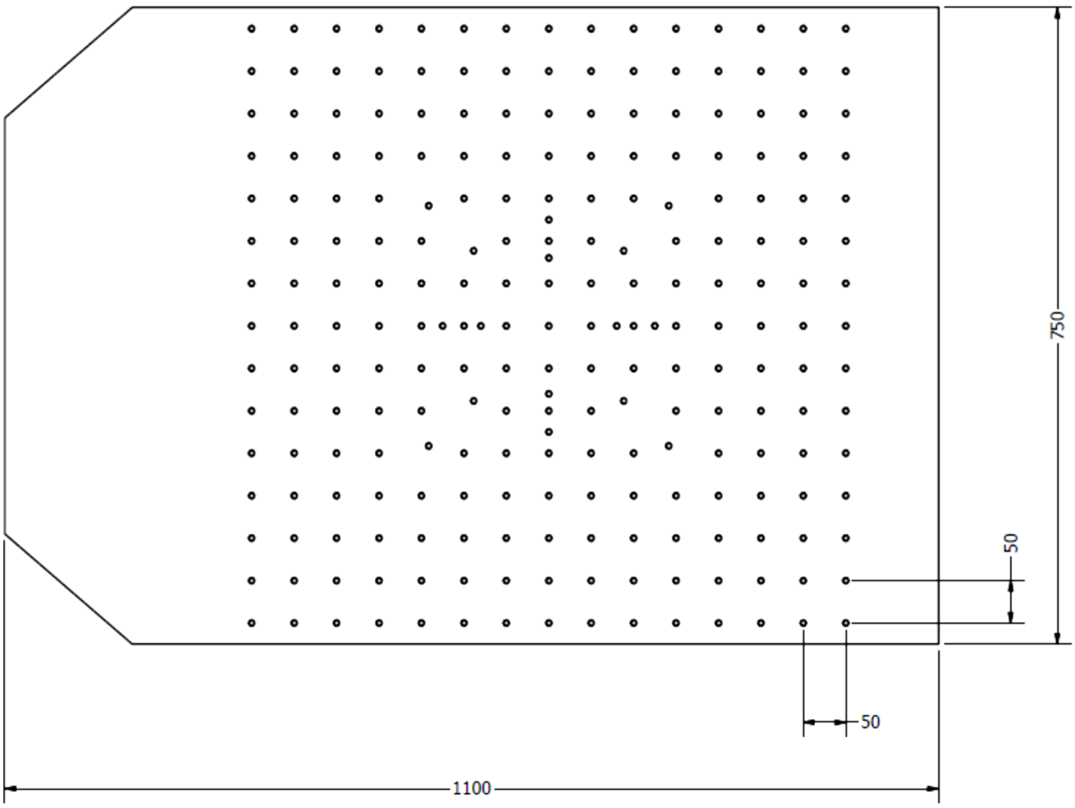

Figure 6-5 ILOT Shaker mount drawing