STUDENTS' SPACE ASSOCIATION

THE FACULTY OF POWER AND AERONAUTICAL ENGINEERING

WARSAW UNIVERSITY OF TECHNOLOGY

CRITICAL DESIGN REVIEW

Project Overview

November 2016

Issue no. 1

Changes

Date	Changes	Pages/Section	Responsible
2016-11-30	First issue of the document	-	Dominik Roszkowski

Published by

Students' Space Association

Warsaw University of Technology, 2016

Project logo by Krzysztof Karaś

Artist's impressions by Marcin Świetlik

Quote as: PW-Sat2 Team, *Phase C Documentation – Critical Design Review – Overview*, Students' Space Association, Warsaw University of Technology, pw-sat.pl 2016

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Abbreviated terms

ADCS	Attitude Determination and Control System
COMM	Communication subsystem
DT	Deployment Team
EM	Engineering Model
EPS	Electrical Power System
ESA	European Space Agency
FDIR	Fault Detection, Isolation and Recovery
FM	Flight Model
GS	Ground Station
LEO	Low Earth Orbit
MA	Mission Analysis
MDR	Mission Definition Review
PDR	Preliminary Design Review
SC	Spacecraft
SKA	Studenckie Koło Astronautyczne (Students' Space Association)
SSO	Sun-Synchronous Orbit
SW	Software
TBC	To Be Continued
TBD	To Be Defined
TBI	To Be Implemented/To Be Issued
TC	telecommand
TCS	Thermal Control System
WUT	Warsaw University of Technology

1 INTRODUCTION

1.1 PURPOSE AND SCOPE

PW-Sat2 project started on 1 January 2013 few months after the PW-Sat had been launched into orbit on Vega maiden flight. In mid-2013 there was a basic concept of PW-Sat2 mission established which – since that time – has changed in many ways.

Aim of this document is to summarize all the changes conducted during the project duration from the system point of view. Many clarifications are required in relation to the design decisions from Preliminary Design Review performed at the end of Phase B in 2015 [PW-Sat2-B-00.00-Overview-PDR] and Phase B Review Item Discrepancy meetings conducted in 2016. We also try to fulfil selected requirements related to Critical Design Review. Project members did their best to comply with ECSS [1] standards, but it is hardly possible in some areas, because the project is realized mainly by the students. Thus, the ECSS requirements were tailored to project capabilities and only selected points stated in [1] and [2] were completed. Many are scheduled to be performed in near future.

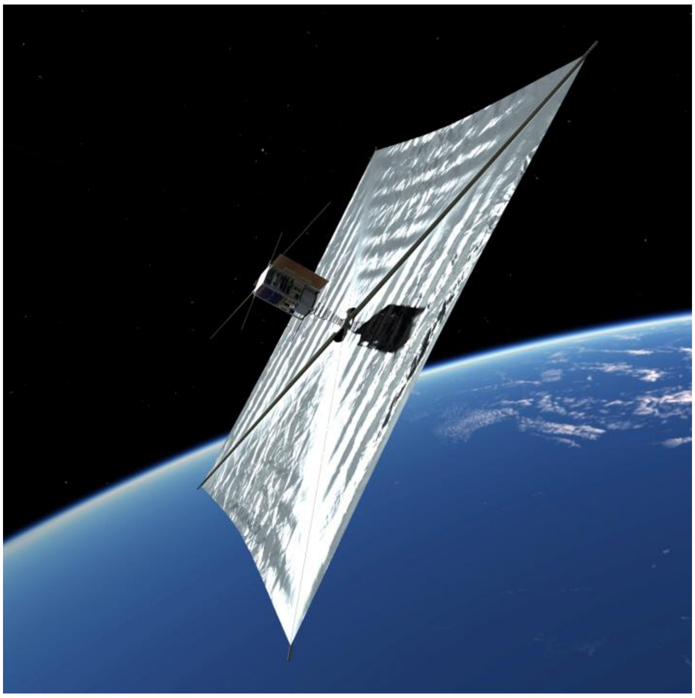


Figure 1-1 Artist's impression of the PW-Sat2 in orbit with its 4m^2 deorbit sail deployed. Author: Marcin Świetlik

1.2 Document Structure

Chapter 1 introduces the document, main objectives of this very overview, documentation structure, reference documents and applicable project documents.

Chapter 2 contains overall PW-Sat2 project description: history, changes, milestones, organizational structure and current status is described in this part. Its aim is to clarify some of the misunderstandings that arose during project duration.

Chapter 3 provides the mission statement and main mission goals wrt satellite.

Chapter 4 summarizes mission plan of the satellite. This chapter contains Mission Plan along with specification of Mission Modes. Detailed mission analyses may be found in [PW-Sat2-C-00.01-MA-CDR].

Chapter 5 presents system overview of the satellite. Both basic subsystems as well as experimental payload are described briefly. Detailed documentation of each of them is available in separate files listed in section 1.3.

Chapter 6 describes briefly philosophy, procedures and facilities of the test campaign of the PW-Sat2. For more details refer to [PW-Sat2-C-11.01-Tests-Plan-Mechanical] and [PW-Sat2-C-11.02-Tests-Plan-Thermal] and respective subsystem summaries.

1.3 Project Documentation Structure

Along with this very document there is a number of other files available – they describe each of the subsystems, specific procedures, or planned test campaign. Most of them was updated and rewritten in Phase C, thus the previous documents should be used as reference only. The documentation structure of PW-Sat2 project was updated to the new scheme as presented in Table 1-1. Please note that only publicly available documents are listed in the table.

In December 2016 all documentation is under unification and editorial changes, so some inconsistency is possible between them. Project members constantly work on the documentation, so potential readers should always check for updates on official website http://pw-sat.pl/en/documentation/. Should you find any obvious contradictions, technical errors or typos, please do not hesitate and write to us a message to pwsat2@gmail.com.

Table 1-1 Documentation structure of PW-Sat2 project as of November 2016

		Phase 0**	Phase A*	Phase B**	Phase C**
Organization		PW-Sat2-0-00.00-MDR	PW-Sat2-A-00.00-Overview-PRR	PW-Sat2-B-00.00-Overview-PDR	PW-Sat2-C-00.00-Overview-CDR
Mission Analysis			PW-Sat2-A-00.01-MA-PRR	PW-Sat2-B-00.01-MA-PDR	PW-Sat2-C-00.01-MA-CDR
Subsystems	ADCS		PW-Sat2-A-01.00-ADCS-PRR	PW-Sat2-B-01.00-ADCS-PDR	PW-Sat2-C-01.00-ADCS-CDR
					PW-Sat2-C-01.01-ADCS-ICD
	COMM		PW-Sat2-A-02.00-COMM-PRR	PW-Sat2-B-02.00-COMM-PDR	PW-Sat2-C-02.00-COMM-CDR
	EPS		PW-Sat2-A-03.00-EPS-PRR	PW-Sat2-B-03.00-EPS-PDR	PW-Sat2-C-03.00-EPS-CDR
					PW-Sat2-C-03.01-EPS-ICD
	OBC		PW-Sat2-A-04.00-OBC-PRR		PW-Sat2-C-04.00-OBC-CDR
	DT		PW-Sat2-A-05.00-DT-PRR	PW-Sat2-B-05.00-DT-PDR	PW-Sat2-C-05.00-DT-CDR
					PW-Sat2-C-05.01-DT-Structural-Analyses
					PW-Sat2-C-05.02-DT-Analytical-Calculations-and-Dynamic-Models
	SunS		PW-Sat2-A-06.00-SunS-PRR	PW-Sat2-B-06.00-SunS-PDR	PW-Sat2-C-06.00-SunS-CDR
					PW-Sat2-C-06.01-SunS-ICD
	CAM		PW-Sat2-A-07.00-CAM-PRR	PW-Sat2-B-07.00-CAM-PDR	PW-Sat2-C-07.00-CAM-CDR
	PLD				PW-Sat2-C-08.01-PLD-ICD
Thermal Control			PW-Sat2-A-09.00-TCS-PRR	PW-Sat2-B-09.00-TCS-PDR	PW-Sat2-C-09.00-TCS-CDR
					PW-Sat2-C-09.01-TCS-Datasheet-v2.3 (spreadsheet)
Configuration					PW-Sat2-C-10.00-CONF-CDR
					PW-Sat2-C-10.01-CONF-MICD

	Phase 0**	Phase A*	Phase B**	Phase C**
				PW-Sat2-C-10.02-CONF-MICD-Drawing
				PW-Sat2-C-10.03-CONF-Bill-of-Materials (spreadsheet)
Tests plans				PW-Sat2-C-11.00-Tests-Plan-Overview (TBI)
				PW-Sat2-C-11.01-Tests-Plan-Mechanical
				PW-Sat2-C-11.02-Tests-Plan-Thermal
Assembly Plans				PW-Sat2-SADS-Assembly-Plan
				PW-Sat2-SAIL-Assembly-Plan
				PW-Sat2-SAIL-Production-and-Folding-Plan
				PW-Sat2-SARM-Assembly-Plan
				PW-Sat2-SATELLITE-Assembly-Plan
				PW-Sat2-SRSM-Assembly-Plan
				PW-Sat2-SunS-Assembly-Plan

* - Polish and English versions available; ** - English version only, TBI – To Be Issued

1.4 Reference Documents

Internal project documents are referred by its name according to the Table 1-1.

[1] „ECSS-E-ST-10-06C Space engineering - Technical requirements specification," ESA Requirements and Standards Division, Noordwijk, 2009.

[2] "ECSS-E-ST-10-03C Space engineering - testing," ESA Requirements and Standards Division, Noordwijk, 2012.

[3] ESA, "Plan for European Cooperating States," 2016. [Online]. Available: http://www.esa.int/About_Us/Plan_for_European_Cooperating_States. [Accessed 20 11 2016].

[4] Innovative Space Logistics B.V., "Environment levels Auxiliary payloads ISILaunch20," 2016-09-06.

1.5 Document Contributors

This document and any results described were prepared solely by PW-Sat2 project team members. We would like to thank all the wonderful people who sacrifice their time and sometimes private life to develop this project – you are the best!

2 Project Description

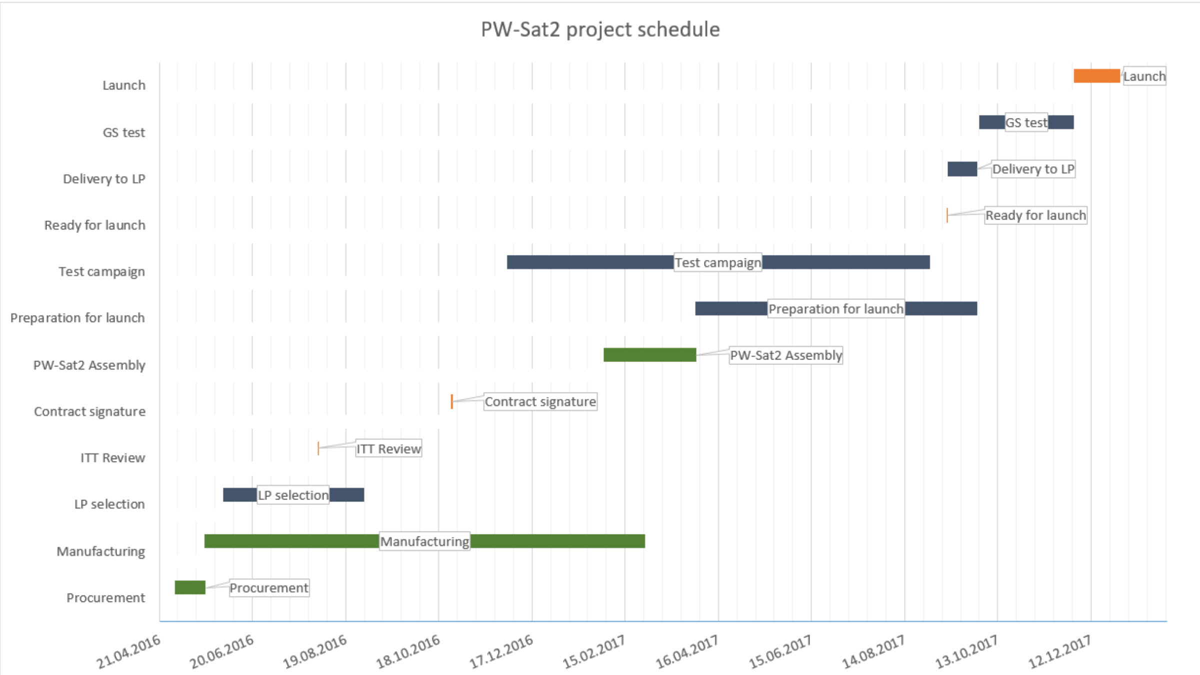
2.1 Introduction – Student Satellite Project

PW-Sat2 is a student satellite project conducted by the members of Students' Space Association (Studenckie Koło Astronautyczne, SKA) at Warsaw University of Technology, Poland. This is an educational project with the main aim of educating new generation of satellite engineers experienced in real satellite design and manufacturing process.

2.2 Current status

The following section describes status of the PW-Sat2 project as of November 2016 in terms of organization, administrative and financial matters.

2.2.1 Timeline



	Procurement	Manufacturing	LP selection	ITT Review	Contract signature	PW-Sat2 Assembly	Preparation for launch	Test campaign	Ready for launch	Delivery to LP	GS test	Launch
Date	01.05.2016	20.05.2016	01.06.2016	01.08.2016	26.10.2016	01.02.2017	01.04.2017	01.12.2016	10.09.2017	11.09.2017	01.10.2017	01.12.2017
Duration	20	284	91	1	1	60	182	272	1	19	61	30

Figure 2-1 General timeline of the PW-Sat2 project (approximate dates)

The project started in the beginnings of the 2013 (January 4, 2013 is recognized as a starting point) and gradually advanced through Phases A and B. In 2013 and 2014 two large recruitment processes took place and the pace of work increased significantly. The initial schedule was exceeded by few months because of the problems with financial budget and On-Board Computer supply. In 2016 Phase B and beginning of Phase C were reviewed by the ESA representatives and some very important changes in project took place. For instance in such categories as mission plan, operation, OBC software, ADCS, test campaign, or thermal control.

2.2.2 ORGANIZATIONAL STRUCTURE

The scheme of the organizational structure of the project is shown in Figure 2-2. Project Manager is a PhD student who is responsible for the administrative and financial affairs. Every team has its team leader, a student who organizes the team meetings and reports to the project managers. Most of the teams also cooperate with the team supervisor and team advisor. The team supervisor is a person who works at the university, science center or company, and supports the team with his or her knowledge in the field related to the team's focus.

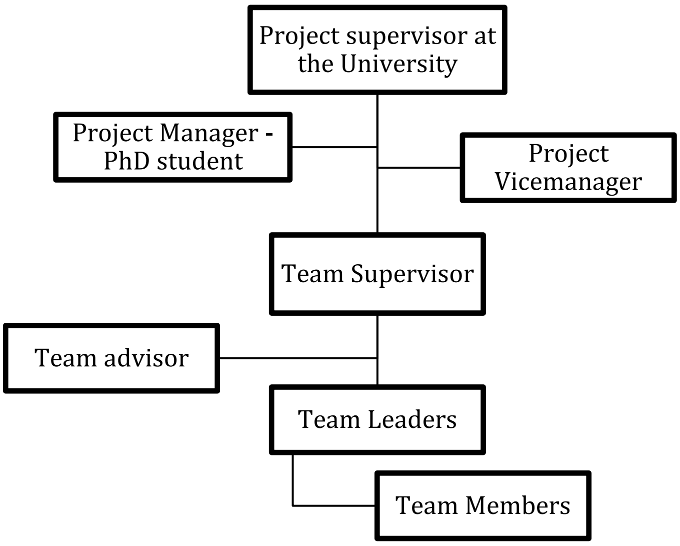


Figure 2-2 Organisational structure of the PW-Sat2 project

2.2.3 MEMBERS

Figure 2-3 Large part of the PW-Sat2 team in the beginnings of 2016

There are more than 30 full-time members working in the project divided into 12 teams. They are students of various faculties of Warsaw University of Technology. Team is supported by employees of Future Processing and FP Instruments, as well by professors and experts of Polish space sector. For more go to pw-sat.pl/zespol/ or pw-sat.pl/en/team/.

Table 2-1 PW-Sat2 project teams (November 2016)

Team	Description	Members
ADCS	Attitude Determination and Control System	6
CAM	Cameras	2
COMM/GS	Communication / Ground Station	3
CONF	Configuration	4
DT	Deployment Team – responsible for deorbit sail structure and retraction system (SAIL), deployable solar arrays (SADS)	13
EPS	Electrical Power System	3
MA	Mission Analysis	2
OBC	On-board Computer	8
OPER	Operations	5
PR	Public Relations/Documentation	4
SunS	Sun Sensor	8
TCS	Thermal Control System	3

2.2.4 Financial Status

Since 2013 up to October 2016 the main funding source was PECS [3]. PW-Sat2 as a successor of PW-Sat was authorized to use the funds granted few years before accession of Poland to European Space Agency. At the beginning of 2016 project received a grant of 180 000 Euro from Ministry of Science and Higher Education. Money was transferred to the European Space Agency, in a form of increased contribution of Poland, paid by Ministry of Development. It is managed by the European Space Agency in a frame of separate program. The funds returned to the Team in the form of contract for the launch of PW-Sat2, issued and supervised by ESA and executed by the PW-Sat2 team.

2.2.5 Launch Status

In the middle of 2016 a tender procedure was organized in order to find a suitable rocket launch. Requirements were prepared and an invitation to open tender was announced via the Faculty of Power and Aeronautical Engineering at Warsaw University of Technology. Two offers with three launch possibilities each were received and the most attractive was chosen – proposed by Innovative Space Logistics B.V. with Falcon 9 as a launch vehicle. The launch is planned on fourth quarter of 2017 from Vandenberg Air Force Base in US.

No.	Company	Variants / Price				Points		
		Launcher	Launch date	Orbit	Net Price	Price	Quality	Total
1a	Tyvak International Srl	PSLV	Q3 2017	500 km near SSO	159 719.24 €	7.85	82.73	90.58
1b		Falcon 9	Q4 2017	500-600 km near SSO	159 719.24 €	7.85	83.87	91.72
1c		PSLV	Q4 2017	650 km near SSO	159 719.24 €	7.85	85	92.85
2a	**Innovative Space Logistics B.V.**	PSLV	Q3/Q4 2017	500-550 km SSO	142 500.00 €	13.60	81.60	95.20
2b		**Falcon 9**	**Q4 2017**	**500-600 km SSO**	**135 000.00 €**	**14.09**	**81.60**	**95.69**
2c		Long March	Q3/Q4 2017	500-600 km SSO	145 000.00 €	13.38	81.60	94.98

2.3 Design History

Since the current status is strongly connected with the previous work it is necessary to describe the mission details presented in Phase A and Phase B reviews.

2.3.1 PHASE 0 (2013)

During the Phase 0 the following payload have been defined, according to the highest priority. Most of the details are described in Phase 0 Mission Definition Review [PW-Sat2-0-00-MDR-Overview].

1. Deorbitation system – square-shaped sail, nitinol as a deploying material.
2. Sun Sensor (SunS),
3. Solar Arrays Deployment System (SADS),
4. Cameras: CAM1 (Main camera, Earth's photographs) and CAM2 (backup camera, registration of the sail deployment).

Basic systems

5. On-Board Computer (OBC) – quasi redundant,
6. Electrical Power System (EPS) – redundant,
7. Thermal Control System (TCS) – passive,
8. Communication System (COMM) – omnidirectional basic, additional directional,
9. Attitude Determination and Control System – (ADCS) – active, magnetic.

2.3.2 PHASE A (2013-2014)

Please be aware that the current (Phase C) state of the satellite may be different than described in previous phases.

During Phase A the subsystems have been confirmed, with the following alterations to the initial designs:

1. Deorbitation system – we gave up on the attempt to use nitinol as the deploying material, due to the following reasons: too low reliability and lack of proper knowledge in nitinol behavior in dynamically changing temperature. Ultimately, it has been decided to use flat springs instead. The prototypes were promising and demonstrated high reliability of the system. A detailed description one may find in the Deployment Team PRR documentation [PW-Sat2-A-05.00-DT-PRR].
2. Sun sensor – SunS – the main assumptions which were defined in Phase 0 have not been significantly changed. The simplicity of the device as well as the fact that it is a previously defined design results in less modifications needed during the continued development. The first prototype tests were made during Phase A. A detailed description can be found in the SunS Phase A documentation [PW-Sat2-A-06.00-SunS-PRR].
3. Solar Arrays Deployment System – SADS – during the Phase A the system has been developed and refined from the initial design. The calculations of the springs have been made, and the deploying mechanism has been designed. The detailed description can be found in the DT phase A documentation [PW-Sat2-A-05.00-DT-PRR].
4. Cameras [PW-Sat2-A-07-CAM-PRR].:

a. CAM1 – after a detailed mission analysis it was decided to **cancel** the camera planned for Earth pictures. Main reason of this decision is the fact that the camera has a low scientific value, therefore it cannot be defined as a relevant scientific payload. With regard to the pictures resolution, its transmission requires S-Band antennas, which cause a higher system complexity of the communication system, as well as a significant growth of the project costs.

b. CAM2 – during the defining of the project success levels it was determined that the CAM2 camera is an integral element of the deorbit system. The camera will verify the correctness of the sail deployment. This camera is physically smaller than the proposed CAM1, and it was designed to capture pictures in low resolution, which will cause 5 times less system charge (the resolution is 3 times smaller than that of CAM1, and the number of bits per each pixel is also 3 times smaller) and will allow to send the pictures by use of the omnidirectional antennas of the UHF/VHF system. A detailed description can be found in the COMM Phase A documentation [PW-Sat2-B-02.00-COMM-PDR] **Warning!** The design of the camera system changes significantly in the Phase C.

Basic systems:

5. On-board Computer (OBC) - quasi redundant,
6. Electrical Power System (EPS) - redundant,
7. Thermal Control System (TCS) - passive,
8. Communication System (COMM) - omnidirectional,

   After the communication system requirements analysis, no need was found to use the communication system in S band. The use of camera CAM1 was closely related with the planning of a high data transfer communication system. Withdrawal from the idea of using CAM1 caused the resignation of the S-Band system.

9. Attitude Determination and Control System (ADCS) – active, magnetic.

2.3.3 PHASE B (2014-2015)

Please be aware that the current (Phase C) state of the satellite may be different than described in previous phases.

During phase B the subsystems have been confirmed, with the following alterations to the initial designs:

1. Deorbitation system – we continue to use flat springs instead of nitinol. Most of the time we spent to check a various types of solutions for this system. A detailed description can be found in the DT Phase B documentation [PW-Sat2-B-05.00-DT-PDR].
2. Sun sensor – most of the assumptions for this device had not been changed since the previous phase. During the Phase B there were proposed a few various geometrical configuration of the Sun Sensor. The

decision of using a reference sun sensor on the satellite had been made. A detailed description can be found in the SunS Phase B documentation [PW-Sat2-B-06.00-SunS-PDR].

3. Solar Arrays Deployment System – during phase A the system has been developed and refined from the initial design. No additional system solutions had been introduced during the phase B. The detailed description can be found in the DT Phase B documentation [PW-Sat2-B-05.00-DT-PDR].
4. Cameras:
    a. CAM1 – during the Phase B we decided to cancel the Camera 1. However, one of the project partners showed its interest in using the free space on the satellite to implement its own camera device. It wanted to test a custom star tracker camera on board PW-Sat2 satellite. The description of the cooperation and technical aspects can be found in the Phase B cameras documentation [PW-Sat2-B-07.00-CAM-PDR]. In 2015 this company decided to resign from cooperation, thus idea for placing star tracker was abandoned.
    b. CAM2 – the purpose of using camera 2 remained the same since the phase A. If the partner had not cancelled the cooperation, he would have delivered the camera for observation of the sail deployment moment. Thus, we had to design and choose the subsystems on our own. During the Phase B the mounting concept had been also evaluated. A detailed description can be found in the CAM Phase B documentation [PW-Sat2-B-07.00-CAM-PDR].

Basic systems:

1. On-board Computer (OBC) - problems due to cooperation failure. New partner joined the project and decided to fund the On-Board Computer and to develop the required software - quasi redundant,
2. Electrical Power System (EPS) [PW-Sat2-B-03.00-EPS-PDR] – custom design tailored for the needs of PW-Sat2 systems – redundant,
3. Thermal Control System (TCS) [PW-Sat2-B-09.00-TCS-PDR] – passive,
4. Communication System (COMM) – [PW-Sat2-B-02.00-COMM-PDR] – omnidirectional UHF/VHF antenna,
5. Attitude Determination and Control System (ADCS) [PW-Sat2-B-01.00-ADCS-PDR] – active, magnetic, supported with set of photodiodes and gyroscopes, no GPS.

2.3.4 Phase C (2015-2016) – Current Status

During Phase C many changes which were necessary to fit in the financial and time constraints had to be applied. None of the is critical to the satellite system, but they show immaturity of the previous concepts. Main differences and important points are described in this section.

- Deorbitation system – The main experiment – a 2 x 2 m deorbit sail made of 6 μm thick aluminized Mylar – will dramatically decrease the life-time of the satellite's orbit. It will be made from durable Mylar foil stretched across four flat springs attached to a custom designed reel. The sail will be coiled and placed in a cylinder with a diameter of 80 mm, and the height of the whole system not exceeding 70 mm. After burnout a Dyneema fiber, the sail will be unlocked and deployed a safe distance away from the satellite.

During the procedure the sail flat springs will expand and assume their original c-shape that will stiffen the entire structure. As a result, the area and aerodynamic drag of the satellite will be significantly increased, accelerating the satellite's deorbitation. The deployment process will be recorded by two on-board cameras. During Phase C additional effectiveness analyses of PW-Sat2 deorbit sail were performed. [PW-Sat2-C-05.00-DT-CDR]

- Sun sensor – consisting of four specially aligned walls with ambient light sensors. It will allow determining the orientation of the satellite relative to the Sun. Its accuracy will be validated by comparison to a second, commercial reference Sun sensor. [PW-Sat2-C-06.00-SunS-CDR]
- Solar Arrays Deployment System – The mechanism will be responsible for holding the satellite's lateral panels during the launch phase and release them prior to the deployment. The release will be activated by a specified telecommand. The wire will be melted only after receiving the telecommand from ground station, previously considered timing system was excluded.
- Cameras – In Phase C it was decided that two VGA cameras (CamNadir and CamWing) (uCAM-II from the 4D Systems) will be mounted on a custom designed frame called Secondary Structure located between electronics stack and deorbit sail container. They will be used mainly to capture the moment of the deorbit sail deployment, but can also be used to photograph Earth silhouette. The structure will be hidden behind the walls of the satellite that have special cutouts to allow cameras visibility. [PW-Sat2-C-08.00-CAM-CDR]

Basic systems:

- On-board Computer – Thanks to the cooperation with Future Processing and FP Instruments the CubeSpace CubeComputer V3 will be used as a main computational unit of the satellite. The main task of OBC is to keep track of the satellite state and to execute planned or demanded tasks. Custom software is developed by the OBC team consisting of Future Processing programmers.
- Electrical Power System – The PW-Sat2's Electrical Power System (EPS) is responsible for power conversion from solar panels, energy storage in battery and power distribution to subsystems. More on this system in [PW-Sat2-C-03.00-EPS-CDR].
- Thermal Control System – The system responsible for stabilizing temperatures across the satellite and assure, that all components will work within their operational temperature limits. TCS consists of active system (built-in heaters in battery pack) and passive systems (radiator, surface painting, second surface mirror). Due to the issues with batteries temperature during phase B, two thin aluminum walls were added at both sides of the satellite to prevent overheating. Additionally, analyses were further expanded to include different albedo at the poles and equator. More in [PW-Sat2-C-09.00-TCS-CDR].
- Communication – The UHF downlink and VHF uplink communications module is responsible for receiving telecommands, sending telemetry and payload data. It has been decided to buy an existing communications module along with an antenna module: ISIS UHF downlink / VHF uplink Full Duplex Transceiver. Main ground station that will be used to communicate with PW-SAT2 will be placed in the Faculty of Electronics and Information Technology. The station is equipped with transceiver ICOM IC-

910H, computer, antenna rotator. Using the experience of BRITE team, we decided to use antennas with cross polarization – Tonna 20818 for VHF and Tonna 20938 for UHF. Software for HAM radio operators for decoding PW-Sat2 telemetry is planned and developed by Softwaremill. More in [PW-Sat2-C-02.00-COMM-CDR]

- Attitude Determination and Control System –The major task of ADCS is pointing the deployed solar panels towards the Sun. Thus the estimation of the attitude with the presence of noise is required. Second task of attitude control system is detumbling, i.e. deceleration satellite's rotational motion after P-POD deployment. More in [PW-Sat2-C-01.00-ADCS-CDR].

The more detailed description of the current status of the subsystems design is provided in next chapter. The most extensive are separate documents listed in Table 1-1.

3 MISSION STATEMENT

This chapter describes the main goals of the PW-Sat2 mission as a satellite.

3.1 MAIN TECHNOLOGY GOALS

PW-Sat2 satellite is going to have several experiments on-board and one of the mission goals is to perform technology demonstrations of the designed solutions.

3.1.1 DEORBIT SAIL TEST

The main experiment – a 2 x 2 m deorbit sail made of 6 µm thick aluminized Mylar – will dramatically decrease the life-time of the satellite's orbit. It will be made from durable foil stretched across four arms based on a flat springs attached to a custom designed reel. The sail will be coiled and placed in a cylinder with a diameter of 80 mm, and the height of the whole system not exceeding 70 mm. After burnout a Dyneema wire, the sail will be unlocked and deployed to a safe distance (~20cm) away from the satellite. During the procedure the sail flat springs will expand and assume their original C-shape that will stiffen the entire structure. As a result, the area and aerodynamic drag of the satellite will be significantly increased, accelerating the satellite's deorbitation. The deployment process will be recorded by two on-board cameras.

From the very beginning of the design process, the system was designed in order to be as easy in use as possible. Effort required during the final satellite assembly has been minimized. The sail subsystem is delivered as a complete device, and only the mechanical mounting and plugging in of the connector is necessary.

The PW-Sat2 mission is an opportunity to test new technique of sail deployment in space environment and to compare its effectiveness with the performed analyses.

3.1.2 SUNS TEST

There will also be a custom designed Sun sensor aboard PW-Sat2, consisting of four specially aligned walls with ambient light sensors. It will allow determining the orientation of the satellite relative to the Sun. Its accuracy will be validated by comparison to a second, commercial reference Sun sensor.

3.1.3 SOLAR ARRAY DEPLOYMENT SYSTEM TEST

Solar Arrays Deployment System is based on torsion springs and will open 2U Solar Panels to an angle of 90°. System is a custom design and allows to deploy Solar Panels on the angle between 0-180° after small modifications. The whole mechanism is simple, reliable and compact – its whole components are placed inside the main structure's rail.

System was designed to not only open Solar Panels to obtain more energy e.g. during SunPointing but also to check custom design working, which can be used in future small satellite's missions.

3.1.4 ELECTRICAL POWER SYSTEM TEST

The EPS of the PW-Sat2 is a custom design by the PW-Sat2 team. Details on the system may be found in [PW-Sat2-C-03.00-EPS-CDR]. The PW-Sat2 mission will be an opportunity to test this design in real life conditions.

4 MISSION OVERVIEW

4.1 INTRODUCTION

This chapter describes the phases of the PW-Sat2 mission in terms of system logic and operations. For Mission Analysis Report activities refer to [PW-Sat2-C-00.01-MA-CDR].

4.2 MISSION PLAN

Authors: Piotr Kuligowski, Grzegorz Gajoch

Total mission duration before the sail opening has been set to the maximum of **40 days**. Short mission duration is considered as required due to the increasing risk of subsystems' failure, especially electronic subsystems utilizing COTS components are of major concern. After the QuadPack separation a 30 minutes time period of communication silence is required. Only after that the communication module is initialized and antennas are deployed. During this period the system tries to perform Detumbling (see [PW-Sat2-C-01.00-ADCS-CDR]). Later on, a nominal experiments stage begins that lasts until the deorbitation system initialization.

If all subsystems work nominally at day 31 the extended mission is planned to perform further tests of the Sun Sensor experiment. It can be shortened in case of problems with power supply or any other problems as the sail opening and deorbit sail technology test is a primary mission objective.

Mission plan consists of top-level mission phases shown in Figure 4-1. The final timespans will be defined in later phases of the mission design. At the moment the Post-Sail activities require extended analysis and experiments with COMM&ANTS [PW-Sat2-C-02.00-COMM-CDR]. The mission planning in terms of OBC software is going to be managed through state management approach.

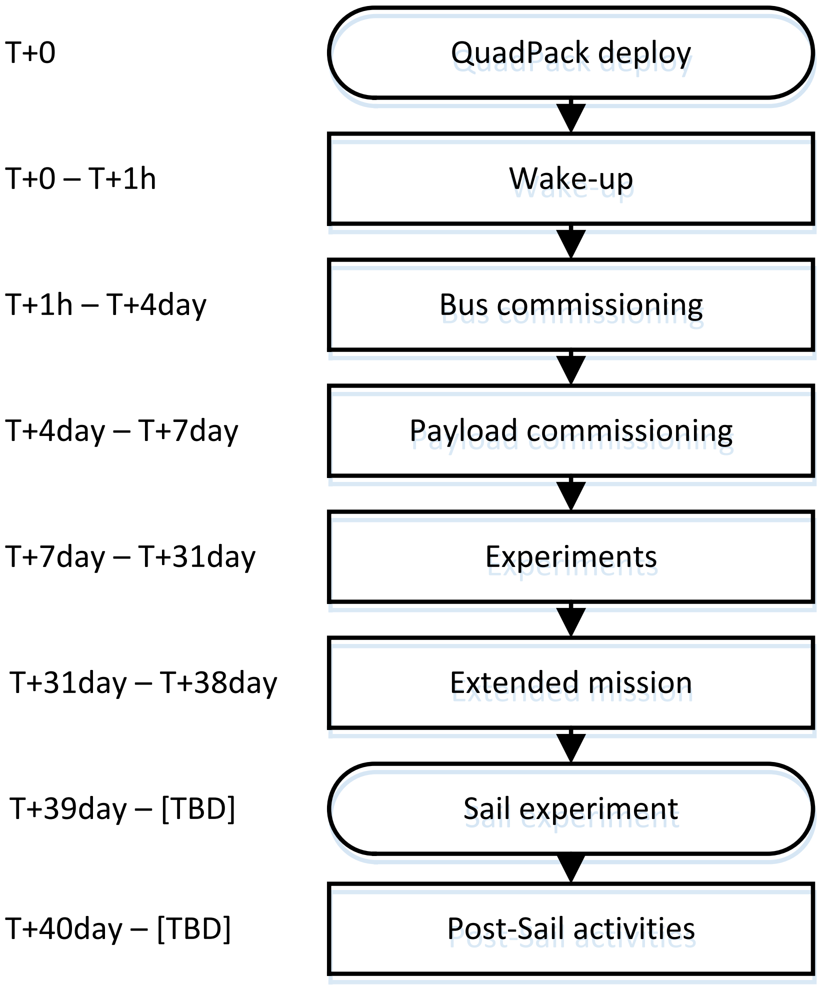


Figure 4-1 Top-level mission plan (2016-11-29)

4.2.1 QUADPACK DEPLOY & WAKE-UP

During Wake-up phase it is planned to record full telemetry every 1 minute. At the end of this phase the ANT module deploys and COMM starts to transmit the beacon. The ADCS detumbling starts.

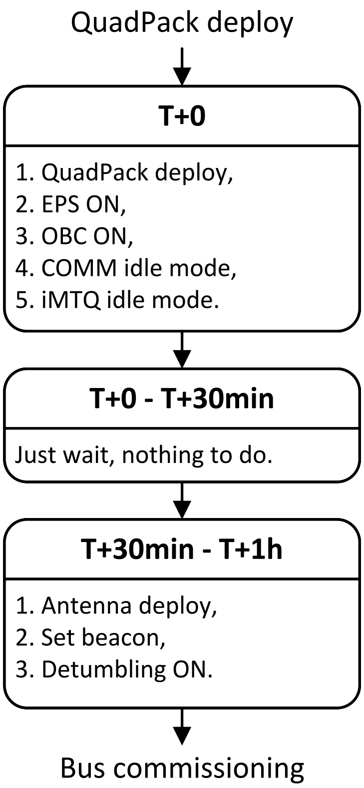


Figure 4-2 Scheme of Wake-up phase

4.2.2 BUS COMMISSIONING

During this phase the basic subsystems of the satellite are checked, full telemetry is requested to be sent.

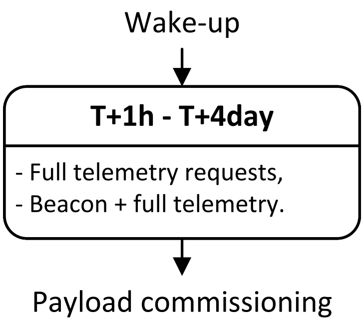


Figure 4-3 Scheme of BUS comissioning phase

4.2.3 PAYLOAD COMMISSIONING

During this phase all the subsystems related to PW-Sat2 experiments are commissioned starting with PLD board. Payload Commissioning may take up to few days.

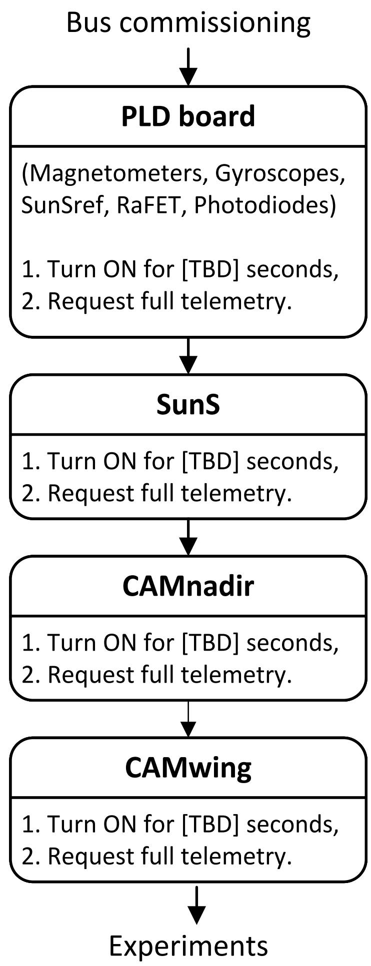


Figure 4-4 Scheme of Payload Commissioning phase

4.2.4 EXPERIMENTS

This phase is devoted to PW-Sat2 on-board experiments. The top-level scheme of experiments to perform is listed in Table 4-1. The exact procedures still require (2016-11-28) deep analysis, but preliminary plans were prepared during November 2016 workshop.

Table 4-1 Scheme of Experiments phase

Time	Experiment
T+7day - T+10day	SunS experiment
T+10day - T+12day	ADCS custom-designed detumbling
T+12day - T+16day	SunPointing experiment
T+16day - T+18day	SADS deploy
T+18day - T+21day	SunPointing experiment
T+21day	SunPointing Enable

Time	Experiment
T+22day - T+23day	CAMs health check
T+23day - T+28day	CAMs photos
T+28day - T+31day	SunS experiment

4.2.5 Extended Mission

If Experiments phase is performed correctly, then the Extended Mission phase drafted in Table 4-2 may take place. During this period most of the operational time is devoted to CAM experiments and trails to receive photos from orbit.

Table 4-2 Scheme of Extended Mission phase

Time	Experiment
T+32day	CAMs health check
T+33day - T+36day	CAMs photos
T+37day - T+38day	Full telemetry requests

4.2.6 Sail Experiment

The grand finale of the PW-Sat2 mission – Deorbit Sail deployment – is scheduled to take place about 40 days after insertion into orbit.

Table 4-3 Scheme of Sail Experiment phase

Time	Experiment
T+39day	Sail experiment
T+39day – [TBD]	1. „Sail experiment” data download. 2. Full telemetry requests.

4.3 Launch and Injection into Orbit

For the details refer to [PW-Sat2-C-00.01-MA-CDR].

4.4 Mission Modes

Authors: Piotr Kuligowski, Grzegorz Gajoch

A very simple approach to mission modes is utilized in order to decrease risk. Two basic mission modes are defined:

- Operational Mode

- Safe Mode

In every mode the OBC counter is counting up to Sail deployment (at the moment assumed 40 days). If OBC is not communicating with EPS for TBD time, then EPS starts power cycle for TBD time. If not succeed, then EPS starts emergency sail deployment.

The general scheme of transitions between them is shown in Figure 4-5.

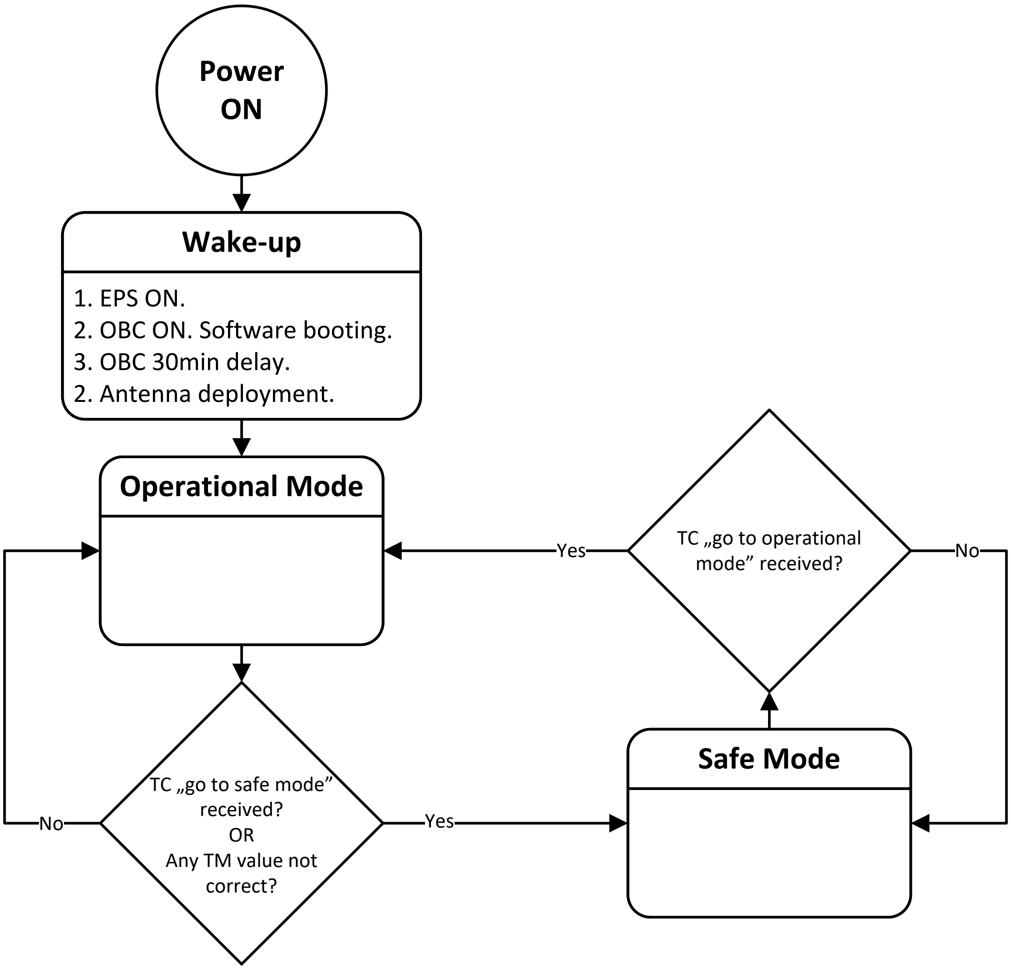


Figure 4-5 Mission modes and transitions between them (November 2016)

4.4.1 Safe Mode

Everything set to OFF except:

- EPS
- OBC
- ANT (set to OFF in case of LOW BAT)
- COMM (awaiting telecommands from GS; transmitting beacon and full telemetry every TBD beacons)

- iMTQ (internal detumbling; set to OFF in case of LOW BAT)

Those subsystems can be set to very low power usage.

4.4.2 Operational Mode

The same subsystems ON as in Safe Mode:

- EPS
- OBC
- ANT
- COMM (beacon and full telemetry every TBD beacons)
- iMTQ [PW-Sat2-C-01.00-ADCS-CDR]

Additionally, experiments set to ON on demand from GS:

- PLD board [PW-Sat2-C-08.01-PLD-ICD]
- CamWing (CAM1) [PW-Sat2-C-08.00-CAM-CDR]
- CamNadir (CAM2) [PW-Sat2-C-08.00-CAM-CDR]
- SunS [PW-Sat2-C-06.00-SunS-CDR]
- SARM (deployment) [PW-Sat2-C-05.00-DT-CDR]
- SRM (deployment of SAIL) [PW-Sat2-C-05.00-DT-CDR]

Telemetry saved to Flash memory – details in [PW-Sat2-C-04.00-OBC-CDR].

4.4.3 State Transitions

Oper -> Safe

Every module is going to be equipped with Fault Detection, Isolation and Recovery (FDIR). FDIR should check if every sensor is in correct range, if not -> Safe. Checks for every channel can be disabled via TC.

Safe -> Oper

On telecommand (TC).

4.5 Ground Stations Coverage During Mission

For details refer to [PW-Sat2-C-00.01-MA-CDR]

4.6 Deorbit Phase

For details on orbital analysis of Deorbit phase refer to [PW-Sat2-C-00.01-MA-CDR]

4.7 DEBRIS MITIGATION

Separate Space Debris Mitigation Report is going to be issued, so in this section only brief description of Debris Mitigation is provided. The details on analysis procedures may be found in [PW-Sat2-C-00.01-MA-CDR].

4.7.1 ORBITAL LIFETIME

Extended analyses of deorbit sail effectiveness were performed comparing the lifetime of selected types of satellites with or without deorbit sail on various altitudes and inclinations (see [PW-Sat2-C-00.01-MA-CDR]).

With the confidence level of 95%, there is a probability of 0.9 that lifetime of PW-Sat2 with opened sail will be shorter than 1.22 years. Lifetime confidence interval for probability of 0.9 is [1.16, 1.29] years.

In case of deorbit sail failure it was simulated that with the confidence level of 95%, there is a probability of 0.9 that lifetime of PW-Sat2 with opened sail will be shorter than 15.97 years. Lifetime confidence interval for probability of 0.9 is [15.75, 16.37] years.

4.7.2 DEBRIS GENERATION RISK

As the sail design does not utilize any pyrotechnics or detachable parts, it is believed that there is no increased risk of additional debris generation related to the nominal operation of the sail mechanism. Potential sail release mechanism failure would result in either a partially opened sail or in a complete failure to open the sail structure, neither of which would generate any loose parts or fragments. The sail material is attached to the flat spring along the entire length, thus even a severe rupture of the material would not result in a separation of the material fragments from the sail structure. As the Dyneema fiber holding the sail is almost completely confined, even the failure of the fiber burning system or fiber break would not cause any space debris generation.

The main purpose of the sail is to prevent orbital debris from staying on orbit for a prolonged time by deorbiting them. Deorbiting with sail happens faster due to the increased area and thus decreased mass to cross-section ration of the satellite. However, increase in the satellite's cross-section area might potentially, contrary to the purpose of the sail, increase the population of space debris by increasing the on-orbit collision probability of the satellite. This phenomenon was studied to make sure that the opening of the PW-Sat2 satellite decreases the probability of on-orbit collision. Debris Risk Assessment and Mitigation Analysis (DRAMA) software package was used in this analysis, in particular Assessment of Risk Event Statistics (ARES) tool. Results show clearly that even though the Daily Collision Probabilities for the Open Sail scenario are one order of magnitude higher than for No-Sail scenario, the shorter lifetime on orbit does not allow the Cumulated Collision Probability to build up and the final CCP is higher for the scenario without sail.

5 SYSTEM OVERVIEW

5.1 BASIC SUBSYSTEMS

5.1.1 ADCS

Control strategy is utilizing set of 3 perpendicular electromagnetic coils called magnetorquers. The ISIS board comprises of 2 rods and 1 air core. Simulation results prove that magnetorquers and spin stabilization controller let the solar panels point the Sun with very good accuracy. On-board magnetometer XEN1210 is used for autonomous detumbling mode.

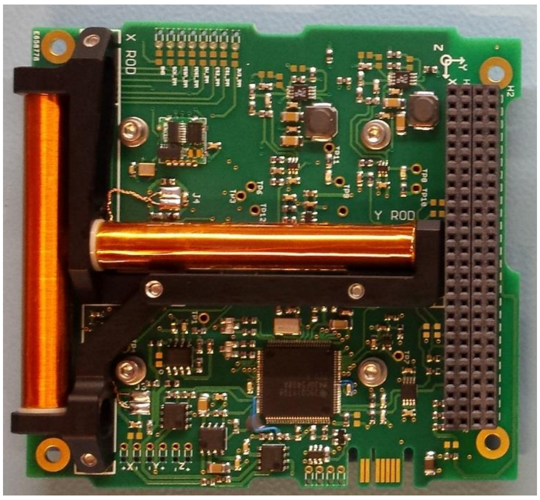


Figure 5-1 iMTQ Board

In Detumbling mode the magnetometer is used. The information from two subsequent samples is integrated to estimate the satellite's angular rate. The control law is simple and robust. More on control of PW-Sat2 attitude in [PW-Sat2-C-01.00-ADCS-CDR].

5.1.2 COMM/GS

The UHF downlink and VHF uplink communications module is responsible for receiving commands, sending telemetry and payload data. It has been decided to buy an existing communications module along with an antenna module: ISIS UHF downlink / VHF uplink Full Duplex Transceiver have been chosen. Detailed description may be found in [PW-Sat2-C-02.00-COMM-CDR].

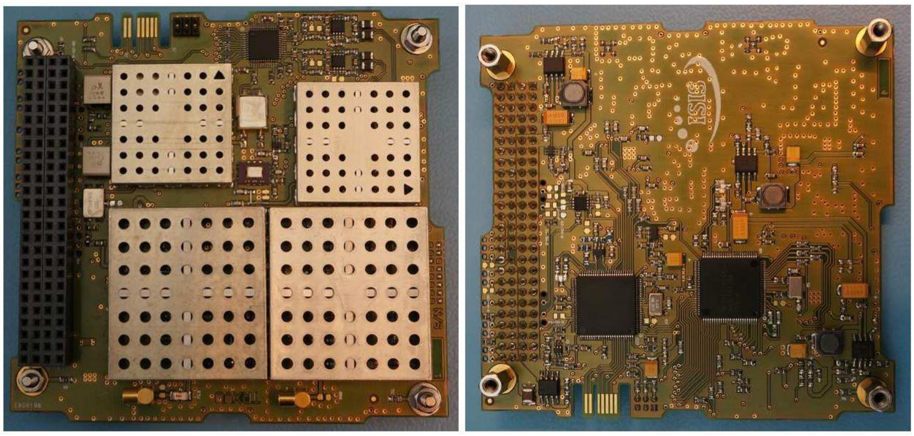


Figure 5-2 Photo of ISIS UHF downlink / VHF uplink Full Duplex Transceiver PCB.

Transceiver will be connected to suitable antenna system from ISIS. Deployment of antenna module is implemented using wires that are burned out by DC current in few seconds and release deployment mechanism. Its subsystems are duplicated – including communication lines and burn-out wires.

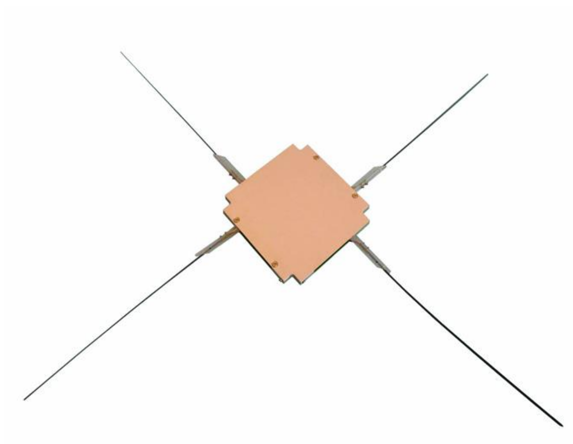


Figure 5-3 ISIS Deployable Antenna System

Main ground station that will be used to communicate with PW-Sat2 will be placed at the Faculty of Electronics and Information Technology of Warsaw University of Technology. The station is equipped with transceiver ICOM IC-910H, computer, system to rotation antennas and TNC to digis modes. Using the experience of BRITE team, we decided to use antennas with circular polarization – Tonna 20818 for VHF and Tonna 20938 for UHF. Antennas will be used with symmetrical splitters. This will eliminate a decrease in the radio signal associated with the rotating PW-Sat2.

5.1.3 EPS

Author: Piotr Kuligowski

The PW-Sat2's Electrical Power System (EPS) is responsible for power conversion from solar panels, energy storage in battery and power distribution to subsystems. To generate electrical power from sunlight, we will use 12 pieces of space qualified triple-junction solar cells. And then the electrical power shall be harvested by a corresponding circuit. To store energy a lithium-ion battery will be used.

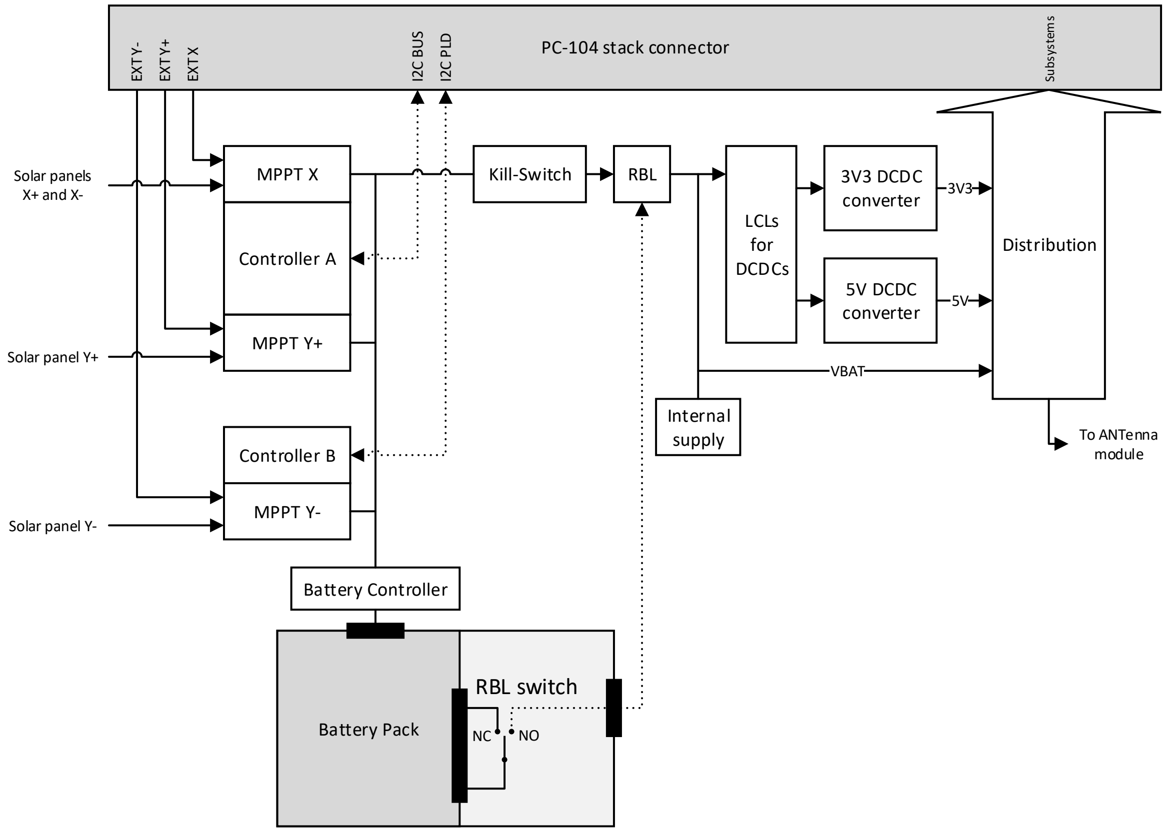


Figure 5-4 A simplified block diagram of EPS

Some subsystems need regulated and protected lines. Those are 3.3V and 5V lines. Unregulated lines shall also be protected. To increase efficiency of solar power conversion the MPPT algorithms are required. The main idea is: one MPPT channel per one solar panel. To achieve high efficiency DCDC converters shall be used.

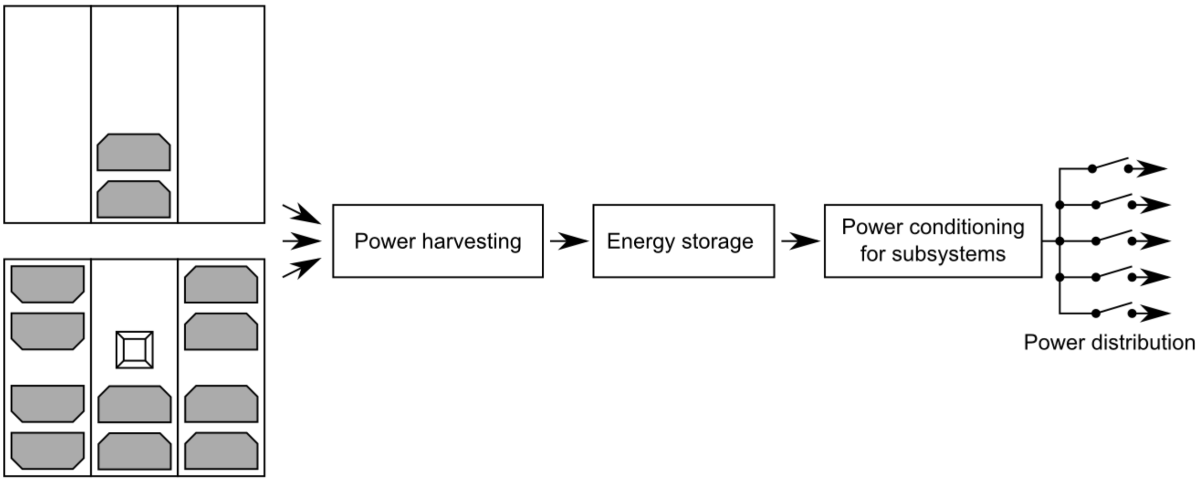


Figure 5-5 Functional block diagram of the system

MPPT regulators are responsible for converting electrical power which is harvested by solar panels. A single MPPT regulator consists of controlled DCDC converter, current and voltage measurement circuits, ADC and DAC converters which are controlled with controller A or B (depends on channel). Solar panels are connected to X+, X-, Y+ and Y- inputs.

In addition, the MPPT regulators may convert electrical power which is provided from EGSE through EXT X, EXT Y+ and EXT Y- inputs. This feature allows to charge the batteries and test the EPS before launch.

Detailed diagram of the MPPT regulators:

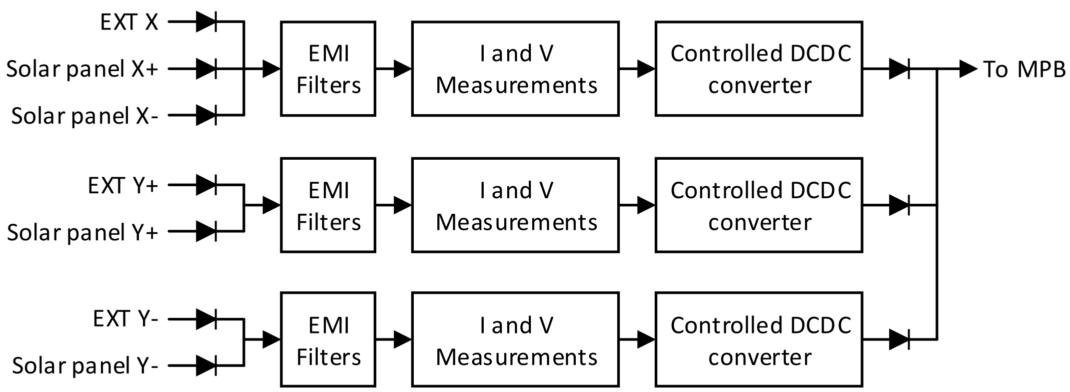


Figure 5-6 MPPT regulators

The controller A is responsible for controlling the MPPT X and MPPT Y+ regulators. The controller B controls the MPPT Y- regulator.

5.1.3.1 ORing diodes for solar panels

Four solar panels are connected to three MPPT regulators. Because of X+ and X- solar panels are on the opposite sides they are ORed to a single MPPT regulator. The Y+ and Y- solar panels have two independent MPPT regulators.

5.1.3.2 Input EMI filters

To decrease EMI susceptibility of the system, the additional input EMI filters were applied. Both differential mode and common mode filters for solar panels were applied. For EXT supply lines just differential mode filters were applied (in EGSE additional common mode filters should be applied).

5.1.3.3 I and V measurements

To perform MPPT regulation, the MPPT regulator measures input voltage and current. These values are available in telemetry.

5.1.3.4 Controlled DCDC converter

This unit contains: a controlled DCDC converter with input and output filters.

5.1.3.5 ORing diodes to MPB

There are three ORing diodes, a single diode for a single MPPT regulator. These diodes are responsible for summing MPPT regulators to MPB bus.

5.1.3.6 Battery controller

This is a power stage for the battery controller feature. Both Controller A and B are responsible for controlling the power stage. Appropriate algorithms maintain the batteries in the suitable conditions.

5.1.3.7 Kill-switch circuit

The kill-switch circuit ensures that the whole system is not active during launch. This circuit consists of two external electro-mechanical switches which are responsible to cut-off subsystems from both battery pack and solar panels.

5.1.3.8 Remove Before Launch circuit

The RBL circuit ensures that the whole system is not active during transportation and storage. This circuit consists of internal cut-off circuits and external electromechanical switch. The electromechanical switch locks the internal cut-off circuits.

5.1.3.9 DCDC converters for 3V3 and 5V

DCDC converters are responsible for converting VBAT raw voltage to 3.3V and 5V. These voltages are supplied for subsystems to the PC-104 stack connector. To protect both Main Power Bus (MPB) and DCDC converters, corresponding input LCL are applied.

5.1.3.10 Controllers

There are two independent controllers in the EPS. To increase reliability of the system, they are completely separated from point of view of electrical connections.

5.1.3.11 Distribution

Distribution contains current measurements, voltage measurements and RLCLs/LCLs for subsystems. RLCL are permanently turned-on, but LCLs are controlled with controller A and B.

The 3V3 line is supplying the permanent 3V3 bus, SunS, CamWing and CamNadir. LCLs for SunS. The CamWing and CamNadir are turned on/off on demand (on a command from OBC).

The 5V line is supplying the permanent 5V bus, ANTenna module and SENS line (which supplies all sensors on PLD board). Both ANTenna module and SENS line are turned on/off on demand (on a command from OBC).

The VBAT line is connected through a RLCL to the PC-104 stack connector as the permanent VBAT bus. The VBAT bus provides supply voltages to deployment LCLs and switches also.

More details on EPS design may be found in [PW-Sat2-C-03.00-EPS-CDR] and [PW-Sat2-C-03.01-EPS-ICD].

5.1.4 OBC

Author: Daniel Dec

5.1.4.1 OBC FM

From Phase A analysis conclusion was made that microcontrollers families such as ARM Cortex-M can efficiently function on LEO for at least a year. OBC flight model was selected to be:

- **CubeSpace CubeComputer**
- EFM32GG280
- RAM (2x1MB + EDAC on FPGA)
- Flash
- I^2C bus (System & Payload)
- SPI bus

5.1.4.2 Development board

For development purposes PW-Sat2 team uses the EFM32GG Starter Kit from Silicon Labs. Differences between MCU are small and should not be preventing us from development.

During development and testing it is necessary to perform a lot of tests on hardware. However using real devices (like COMM, EPS, SunS) will be very ineffective as it is hard (if not impossible) to control test environment. That problem can be solved by using technique called *"mocking"* by replacing each device by simple version can exposes the same interface but can be configured to behave exactly in the way it is needed providing predictable test environment.

In case of OBC I^2C bus is used to communicate with all external devices. That fact allows us to simplify development & test environment by using single device that acts as a bridge between I^2C bus and PC where actual mocks of devices are running. Using that approach gives very flexible and simple solution.

5.1.4.3 OBC EM

There is development ongoing on engineering model of OBC much closer to the FM. The purpose is to use the same types components and connections which is closer to the original OBC design, (development model is not 100% the same) especially with the same CPU and memory. Other factor to take that decision is to not degrade original flight model memory. One thing which would be different comparing to the flight model it to skip FPGA component, however from the functional point of view it is transparent and should not have a big impact on the overall solution. It will be measured delay time required for FPGA and it will be introduced in the engineering model if it is the case. Below it is diagram to present logical schema of engineering. This model would be designed and developed by FP Instruments.

5.1.4.4 OBC software architecture

Target platform of OBC software is FreeRTOS. Logically high-level architecture could be split to be presented at the following view where at the top there is a main functionality (code to control mission) and lower layers below like modules, service buses, memory management, drivers to the hardware.

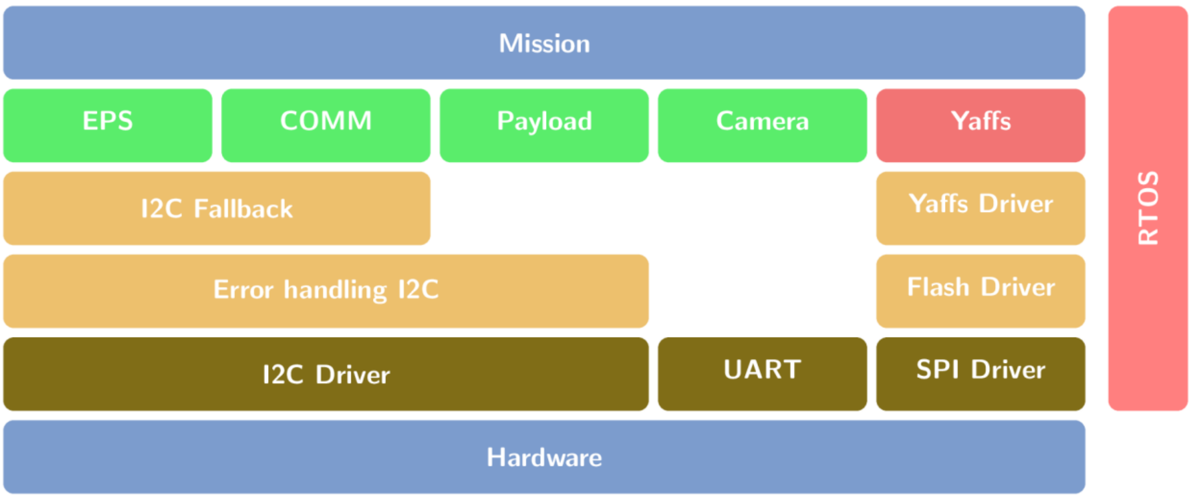


Figure 5-7 High level OBC architecture

More details on mission management, hardware and tests of OBC may be found in [PW-Sat2-C-04.00-OBC-CDR]

5.1.5 CONFIGURATION

Author: Kamil Gajc

Structure, as it was assumed in the initial design, consist of 3 main frames. All structural elements are depicted on Figure 4-5. Definition of axes, which overlap with axes of Quad-Pod, are presented on Figure 4-5 as well. The frames are joint together by 4 screws ISO10642 M3x8, 2 on each side. Frame screw holes will contain Helicoils® M3x3mm inserts in order to increase strength. Contact surfaces between X+ Z- and X- Z- frames have different designs, which prevents inappropriate assembly of the structure. From Z+ side deorbit sail container in a support for the whole structure. This configuration stiffens the satellite and enables to withstand loads occurring during launch and operation on the orbit. Additionally, there was designed secondary structure (dark orange in Figure 5-8) which supports PCB stack and carries loads to the main structure. Secondary structure is also an interface for two cameras.

Primary structure is also an interface for many elements on the satellite, such as PCB stack, SADM, 1U Solar Panels, Sun Sensor, Sail container and Secondary Structure. Structure positions them and is an stiff support for elements. Main structure is a mounting for kill switches and their rods as well.

More about the PW-Sat2 structure may be found in [PW-Sat2-C-10.00-CONF-CDR].

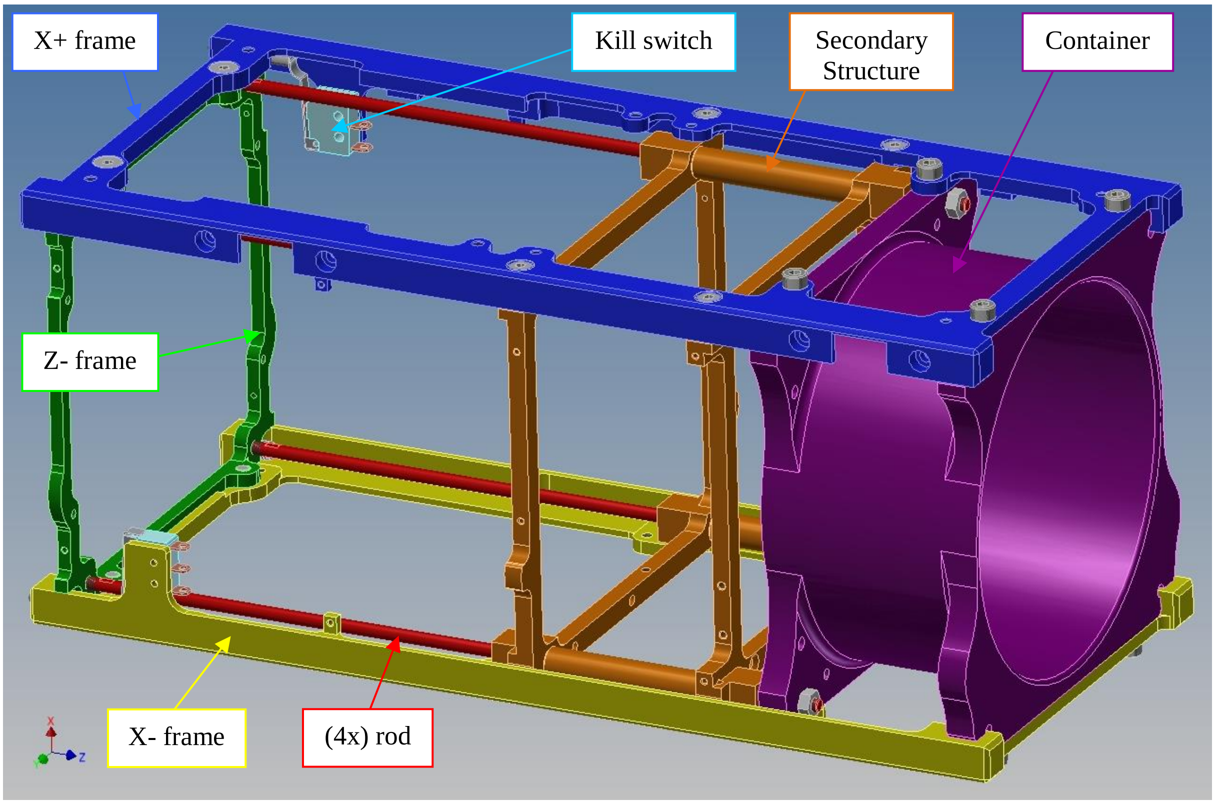


Figure 5-8 Structural elements of PW-Sat2 and definition of axes

5.1.6 TCS

Author: Alan Budzyński

Due to the nature of the space, and its extreme conditions, a thermal analyses need to be performed to check, if the current design does meet the temperature limits of the components. If the results are not satisfying, an appropriate solution needs to be applied to counteract undesired temperatures.

Currently, the satellite does not depend on the active systems to achieve thermal comfort, as the results suggests that the temperatures are within the operational limits. Previous issues were solved using a thermal barrier made of thin aluminum wall, under the unopened solar panels, to prevent overcooling of the components in case of eclipse or during nominal conditions (constant pointing to the Sun), and to prevent overheating caused by solar insulation in case of uncontrolled rotation of the satellite. MLI was not accepted as a thermal barrier due to its overly insulative properties, causing the system to overheat.

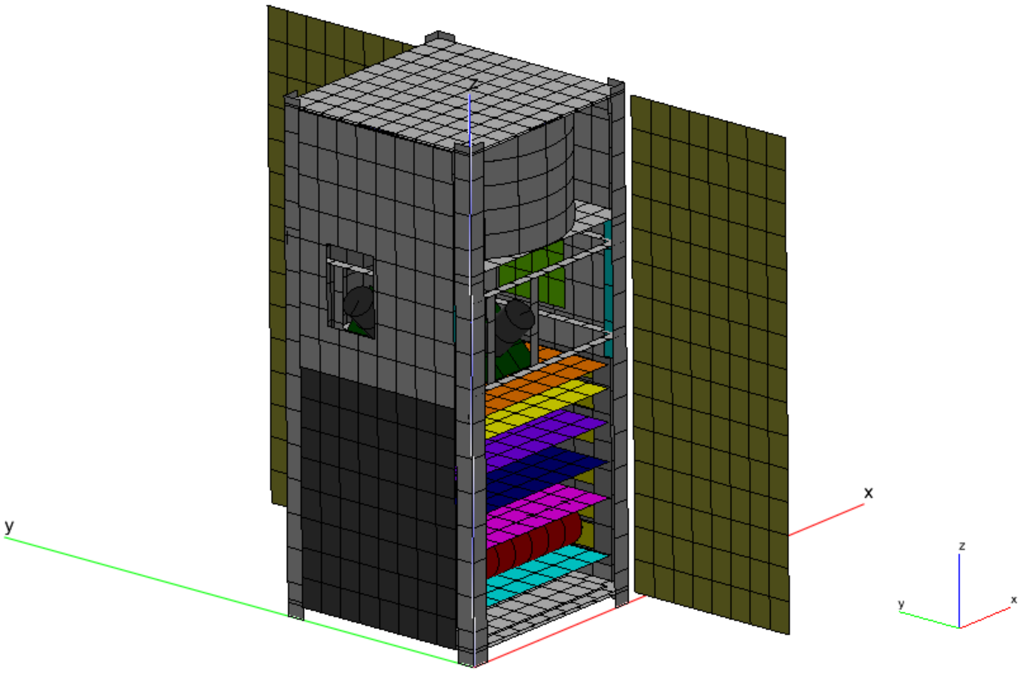


Figure 5-9 Geometrical model of the satellite used in thermal simuation (aluminum walls not included)

Analyses were performed for 4 modes (which are considered to be a basic modes or most probable one) for two different models – the one where solar panels are open, and the one with closed panels. In total 8 analyses were performed for an orbit provided by the launcher.

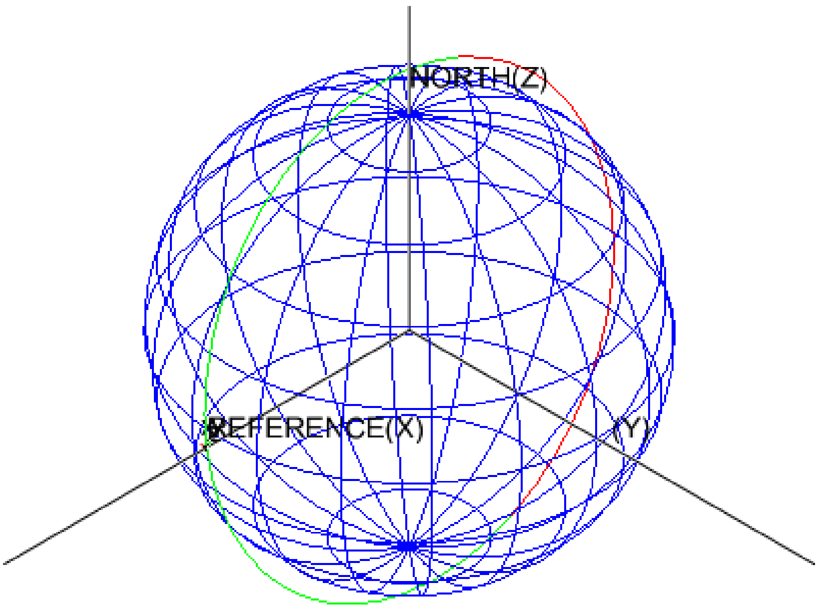


Figure 5-10 Visualisation of the orbit used in thermal simulations

Even though, minimal occurring temperatures do satisfy the limits, a redundant, built-in heaters are included in most crucial components (i.e. batteries) to prevent unforeseen situations.

5.2 PAYLOAD

5.2.1 SAIL (+SRM)

Author: Maciej Kania, Ewelina Ryszawa, Dominika Rafało et al.

PW-Sat2's 2U design guarantees that the deorbit sail system can successfully fit into every structure of a satellite following CubeSat standard. Fully assembled deorbit sail subsystem is placed in an aluminum container with dimensions of 80 mm diameter and 51 mm height. After adding the 10 mm high Sail Release Mechanism (SRM), the whole subsystem takes up to 0.6 U CubeSat volume and weighs about 600 grams. The deployment of the system is based on a 300 mm long conical spring, while the unwinding of the structure is provided by the deployment of flat springs. In the stowed position, the sail is wrapped around the cylindrical reel and held between two limiting plates.

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 on the Dyneema. Additional kick-off springs, as well as inclined surface of contact on reel, allows easy reel release. The mechanism is equipped with a switch for the release confirmation and a PT1000 temperature sensor, checked upon request.

Figure 5-11 Unfolded, full-scale prototype of the sail

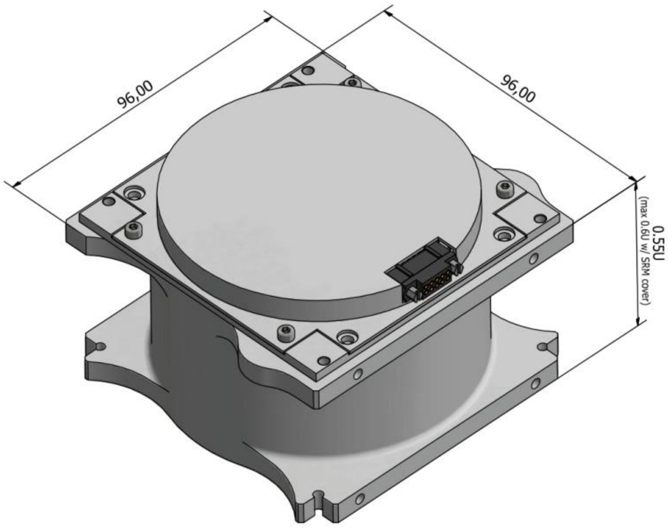


Figure 5-12 Final assembly of deorbit sail container and Sail Release Mechanism, main system dimensions shown

On orbit, after the deployment command, the Dyneema fiber which keeps the system in the closed position is burned 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. Similar solutions have repeatedly been tested in space missions and allow maintaining the system in a folded state for a prolonged time (e.g. on Rosetta mission).

The flat springs are held in sleeves made of Mylar and are attached to the main sail surface along the diagonals of a square. Such attachment ensures that even in the case of damage to the material near the sail arms, the effective area will not change significantly.

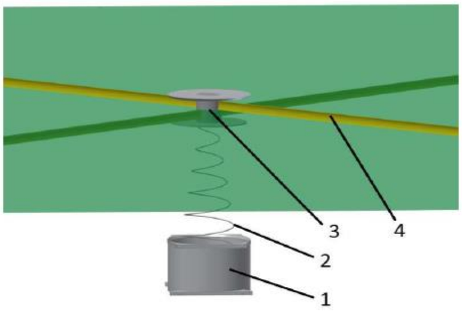


Figure 5-13 Close-up view of deployment mechanism: (1) sail container, (2) - conical spring, (3) - sail reel, (4) - flat springs (sail arms)

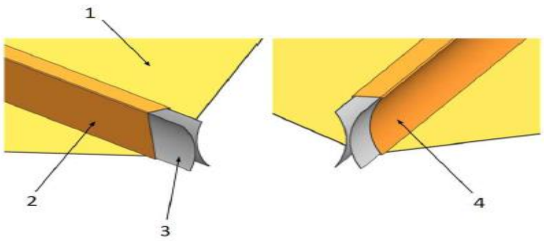


Figure 5-14 Flat springs in pocket; (1) - sail surface, (2) - spring "pocket" (unstuck side), (3) - flat metal springs (sail arms), (4) springs "pocket" (side stuck to one of the flat springs)

Mechanism results in low power requirements. There is no need for a dedicated controller for the system. The deployment process is activated by a standard Latch-Up Current Limiter (LCL), which is named “main LCL”. In case of failure of the “main LCL”, the “redundant LCL” will be activated. For PW-Sat2 mission, the EPS provides also an option to deploy the sail (based on on-board timer) if every other command should fail to do so. Following the Dyneema wire burning, the sail system does not need any electric energy to finish its deployment. 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 2W in time 10sec < t < 1min. For the trigger there are two redundant resistors used.

The whole process of releasing the sail impacts neither any subsystem nor any other satellites from an electromagnetic interference (EMI) point of view. It shall be noted, that it does have impact in other areas, however. A fully deployed sail may cause problems with communication of nanosatellites using omnidirectional antennas, and would require specific analyses for a satellite to ensure it will avoid the problem.

Reliability of the system is provided by using safe, space proven materials (PEEK, Aluminium alloys, Mylar foil, adhesives and Mylar foil with space heritage), and a detailed test campaign for the whole system as well as software and system logistics to send the command. All materials used are compatible with CubeSat Standard (e.g. the system does not require the use of any pressure vessels).

5.2.2 SADS

Author: Katarzyna Ciechowska

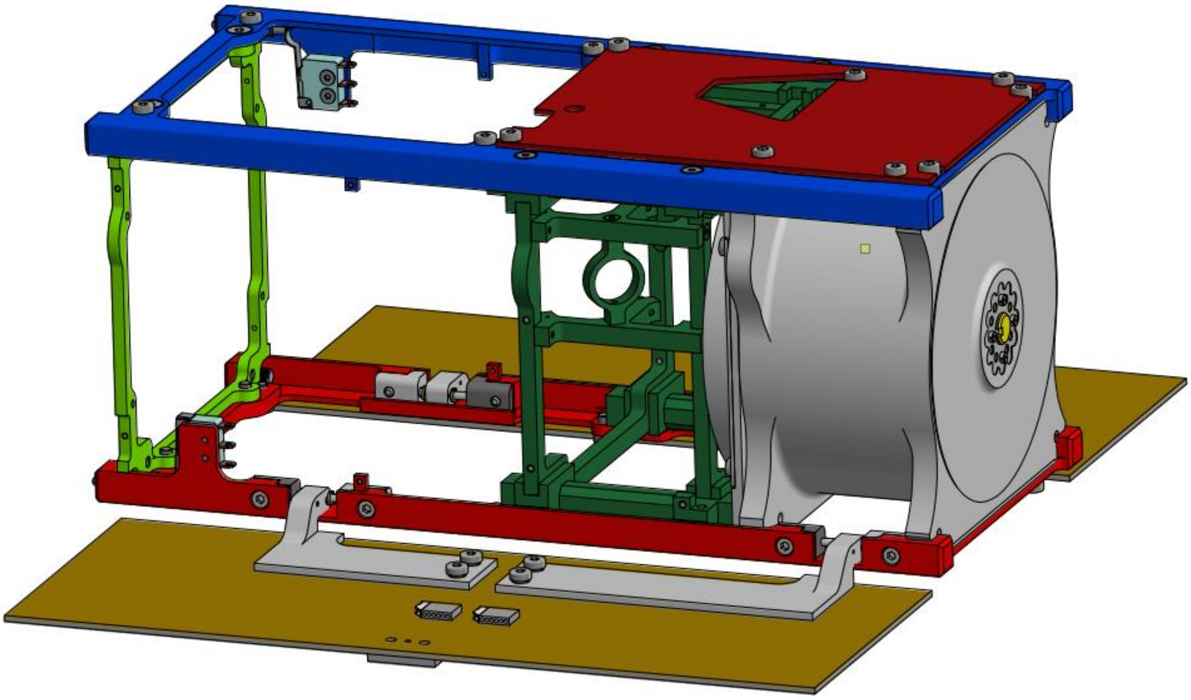


Figure 5-15 View of the Solar Arrays Deployment System and satellite main structure

While the satellite launch into orbit and in the initial phase of the mission the solar panels are closed (adjacent to the Y+ and Y- walls) – Dyneema wire is attached to the free ends of the panels and immobilizes them. Torsion springs placed in the panel's hinge are subjected to pressure (the angle between the free ends of the springs is 90°). Satellite receives a signal to open the panels at some specified time point (see Mission Plan) – electric pulse is send to the resistors touching the Dyneema wire. As a result the resistors heat up and the wire is burned. Torsion springs are opening the panels and they stop at position of 90° on the rail surface. Residual torque causes a continuous spring pressing and prevents the closing of the panels. Motorization margins for torsion spring was performed to ensure the necessary torque at the end of the Panels' movement. This analysis incudes friction torques on hinges and wires connecting Panels to the EPS (also measurement of the friction torque in low temperatures, ≈-50°C were made).

5.2.3 SunS

Author: Mateusz Sobiecki

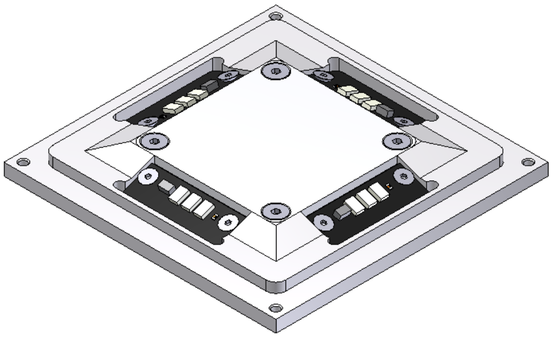
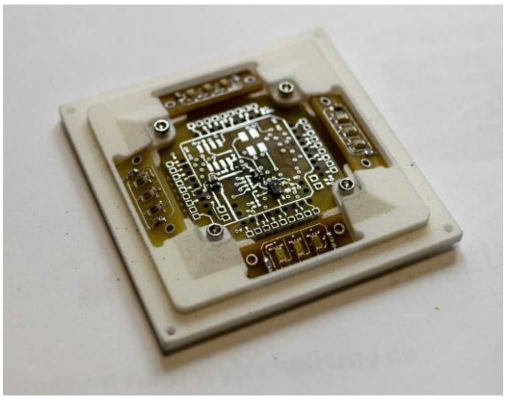



Figure 5-16 Sun Sensor - CAD model on the left and prototype on the right

The Sun Sensor experimental device is presented in the Figure 5-16. It consists of four PCB boards with Ambient Light Sensors and a main electronics board, mounted to the aluminum case. Signals of the light intensities on the four sides of the Sensor are to be calculated to get the angular position of the Sun. The Sun Sensor performance will be verified on the ground by comparison with the reference Sun sensor readouts.

5.2.4 CAM

Author: Mateusz Sobiecki

On board the satellite there will be two the same standard board cameras, mounted to the Secondary Structure, both directed towards the Sail, for the Sail structure's performance visual verification. Cameras will use different lenses, with different field of view (76° and 116° diagonal). One of the cameras will be placed behind the deployable solar array (CamWing), the other behind the CAM wall (CamNadir). They will operated by the OBC through the Payload board, were the cameras will be connected. The cameras operation will be switched between them by the OBC and controlled by the Ground Station operations.

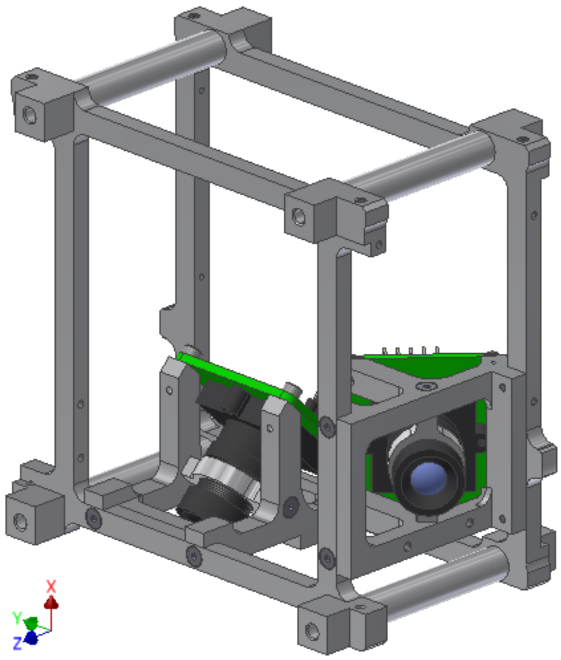


Figure 5-17 Cameras mounted to the Secondary Structure

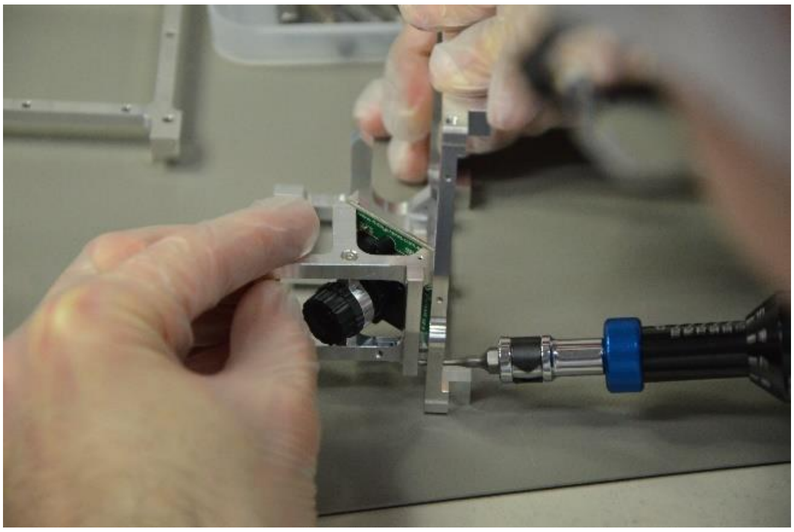


Figure 5-18 Secondary Structure during tests

6 TEST CAMPAIGN

Authors: Inna Uwarowa, Ewelina Ryszawa

6.1 INTRODUCTION

Statistics show that student satellites failure rate is very high[1]. Therefore, lot of attention has been paid to and a lot of effort has been put into reliability of the design. In parallel subsystems design by the Team have been designed to be easy to prototype and test on the early stages of the design. From the early phases of the project a thorough test campaign has been planned to validate the design before launch. Several large testing workshops were conducted in order to come up with the complete test campaign plan and schedule. As this is on-going work the extensive report will be published in following months and will be updated along with the performed tests. The specific tests are described in relevant subsystems CDRs. The overall test plan is described in [PW-Sat2-C-11.01-Tests-Plan-Mechanical] and [PW-Sat2-C-11.02-Tests-Plan-Thermal].

Subsystem which are designed by the PW-Sat2 team were all prototyped and tested from the very early stage of the design. All of the commercial subsystems were tested by their respective manufacturers. Nonetheless, all of the subsystems will go through additional environmental and functional tests during the PW-Sat2 test campaign. The test campaign will also include the tests of the software.

6.2 TESTING PHILOSOPHY

The general test philosophy assumes tests of both qualification and acceptance model. Basically this will require double budget for a flight model components, since QM shall be built with the same components as a FM. Due to the financial constrains the team cannot effort having both QM and FM. The components purchased from external providers are in flight version and in only one piece. Therefore for the FM test campaign the team will follow Proto-flight (PFM) philosophy.

[1] Swartwout, Michael. "The first one hundred CubeSats: A statistical look." *Journal of Small Satellites* 2.2 (2013): 213-233.

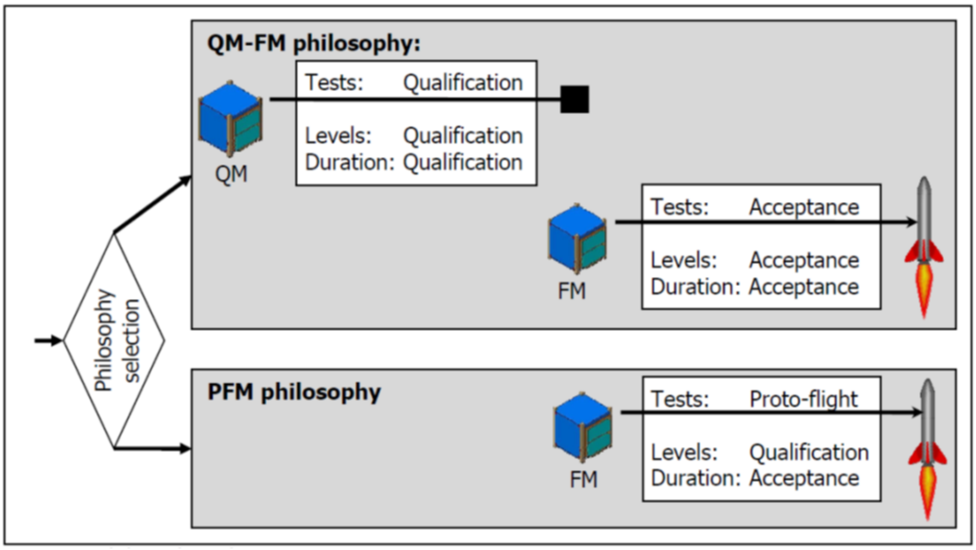


Figure 6-1 Satellite testing philosophies [4]

Due to the launch provider constrains for PFM testing some of the testing requirements will be taken from QM and the other from FM, therefore a PFM is kind of mix of QM and FM testing philosophy.

As mentioned before, the PW-Sat2 satellite is developed in Built&Buy philosophy. Most of the electronics PCB are purchased from external provider (it total 5 PCB was purchased). However, the mechanical parts are in 100% designed by the team. This means that practically all the mechanical parts had been manufactured more than ones as a prototype and pre-flight versions. This allows us to develop additional model – **Structural Thermal Model** (STM) – which will contain identical to the flight versions mechanical parts and similar to FM electronics parts (to simulate mass and thermal properties). Therefore QM testing will be performed on PW-Sat2 STM and PFM on PW-Sat2 FM.

The overview of the tests required for each model is presented below in Figure 6-2.

Description	Ch.	Qualification	Acceptance	Proto-flight
Acceleration (quasi-static)	2	Required	Not required	Required
Resonance survey	3	Required	Required	Required
Random vibration	4	Required	Required	Required
Shock	5	Not required	Analysis required	Analysis required
Bake-out	6	Not required	Required	Required
		PW-Sat2 STM		**PW-Sat2 FM**

Figure 6-2 Overview of the required test for PW-Sat2

6.2.1 ENVIRONMENTAL TEST PLAN

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

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

- 2nd - SAIL test campaign

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 6-3 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 is the reference test for the deployment after vibrations (Functional test II) and TVAC (Functional Test III).

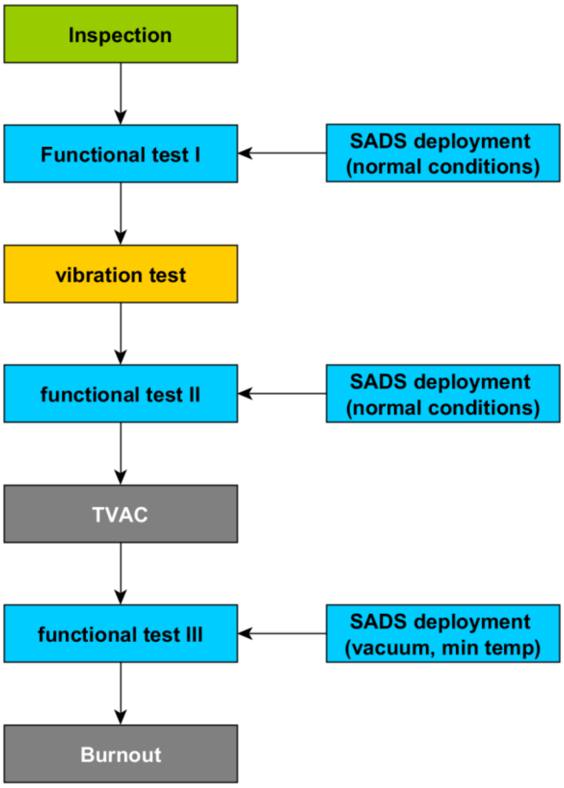


Figure 6-3 PW-Sat2 satellite environmental and mechanism functional testing

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 6-4 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).

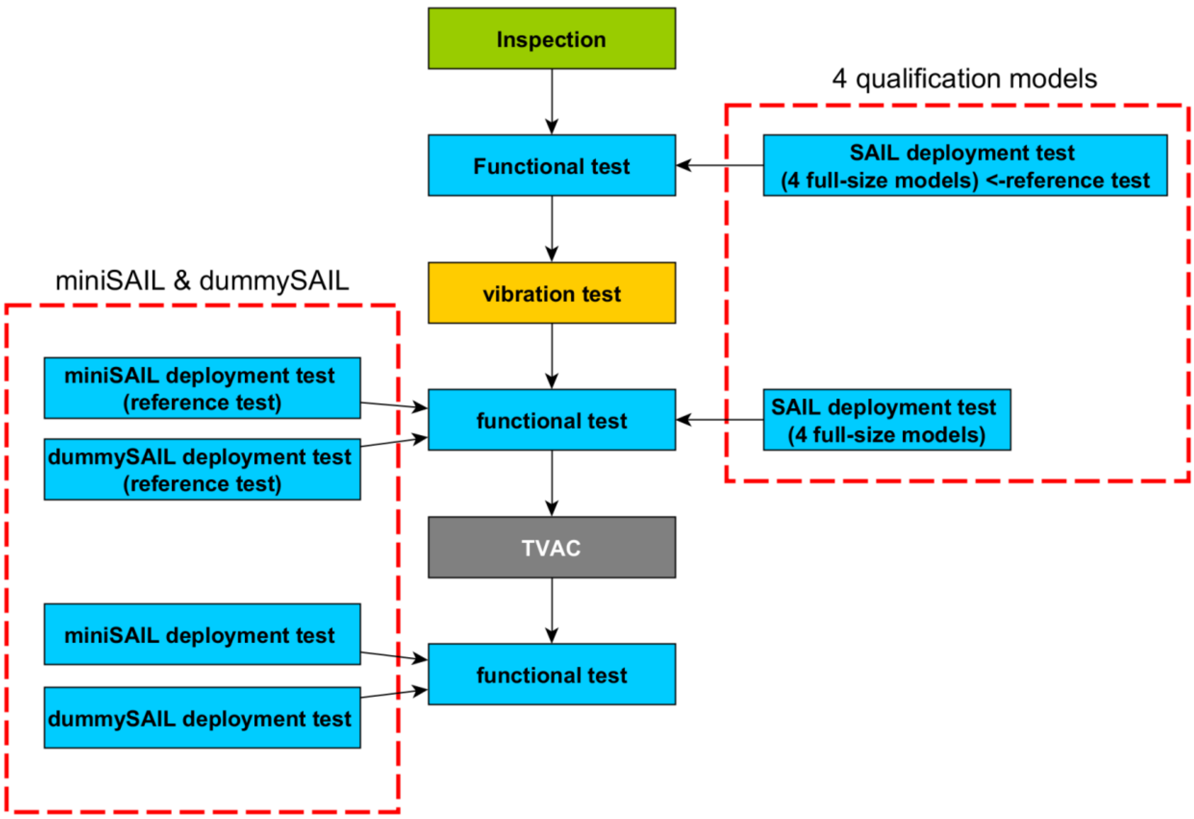


Figure 6-4 SAIL Test campaign

6.3 TEST FACILITIES

There are few major test facilities taken into account in test planning:

- Space Research Centre of Polish Academy of Science (CBK PAN)
- Warsaw University of Technology (cleanroom on Mechatronics faculty
- Istanbul University of Technology (ITU)
- Śląskie Centrum Naukowo-Technologiczne Przemysłu Lotniczego Sp. z o.o.
- Instytut Lotnictwa (ILOT)

The main facility to perform TV test is Thermal Vacuum Chamber, available in Space Research Centre Polish Academy of Sciences (CBK PAN). 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. More information about TVAC test can be found in Test Plans for subassemblies

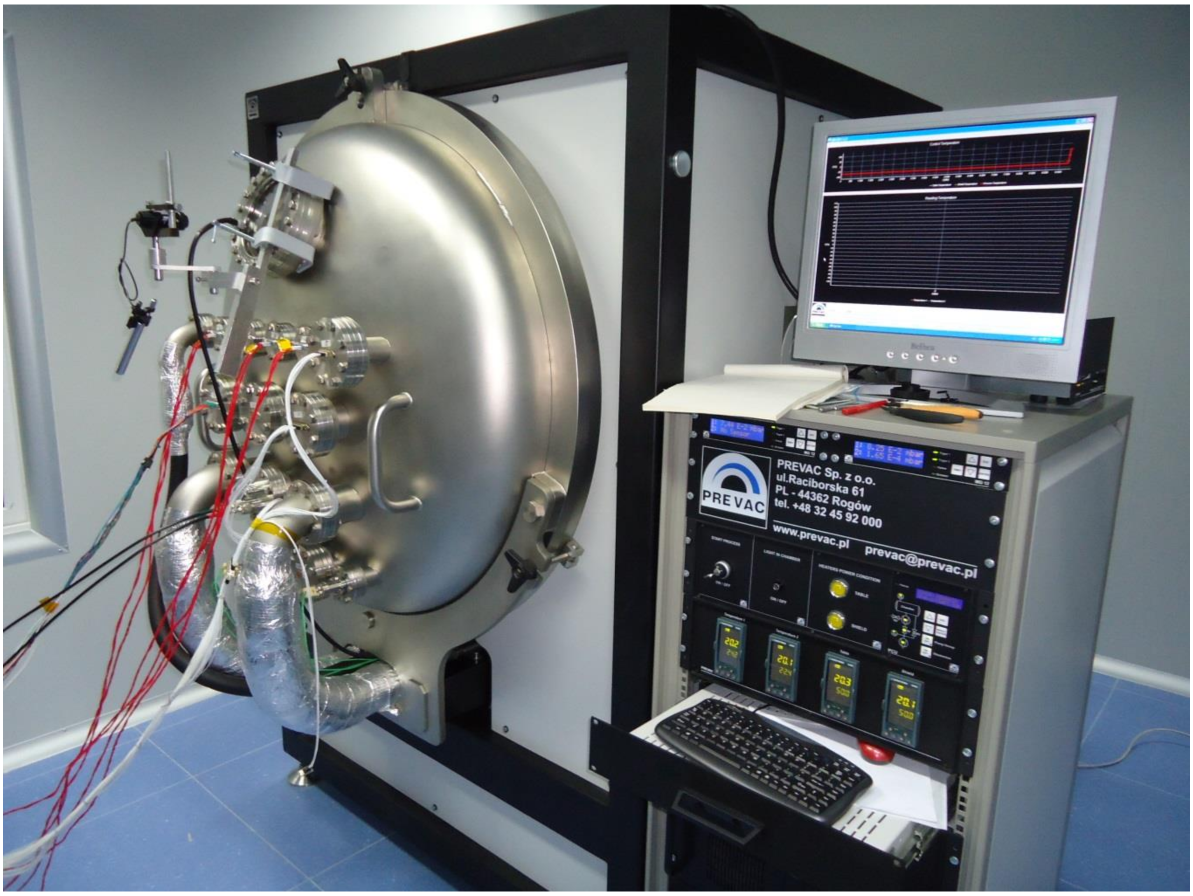


Figure 6-5 Thermal-Vacuum Chamber in CBK PAN

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:

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

Table 6-1 ILOT shaker properties

Figure 6-6 ILOT shaker system

Appendix A COOPERATION WITH COMPANIES

Building of the satellite is a complex and expensive task, especially for student teams. It became necessary to look for both know-how and necessary funds outside the University. Many companies were asked to support the project in various ways. Some companies brought in the know-how from their parent foreign companies, already experienced in space industry. Other companies shared some of their products or services free of charge or borrowed the Team some equipment, also free of charge. Finally, some companies joined our team taking responsibility for some of the tasks, this includes our strategic partner which also funded our OBC and keep the financial support of the project.

The main strategic partners of the project are Future Processing and FP Insturments from Gliwice, Poland.

Since the project kick-off Poland joined ESA and established a national Space Agency. Influx of funds to the Polish space industry resulted in the rapid increase in the number of companies in Poland interested in entering this sector. PW-Sat2 is currently a unique project in Poland as it is the only project of the whole spacecraft that is beyond feasibility study and not yet operational. This creates the opportunity for the companies willing to enter the space industry to learn and gain valuable experience during their cooperation with the Team. Other companies benefit from the access to the pool of enthusiastic young graduates whom they may employ in the future. Finally, there are companies which cooperate with the project as the part of their CSR or marketing strategy. No matter what may be the potential gain for the company in the cooperation, the main common motivations are always the willingness to support young people's education, and the fascination with Space.

Table A-1 List of companies cooperating with PW-Sat2 project

No.	Company	Team	Kind of support	Status
1	Future Processing	OBC, OBSoft	strategic partner of the project, OBC software development	In progress
2	FP Instruments		strategic partner of the project	In progress
3	Agencja Rozwoju Przemysłu	PR	partnership agreement	In progress
4	Omax Waterjets	SunS, DT	solar cells cutting, structural elements	In progress
5	SoftwareMill	COMM, OBC	software for Ground Station, software for OBC	In progress
6	ABM Space	ADCS	ADCS algorithm tests	In progress
7	Laboratorium Szybkiego Prototypowania (WIP PW)	PR, DT	SLS 3D printing	In progress

8	Śląskie Centrum Naukowo - Technologiczne Przemysłu Lotniczego	DT	components manufacturing, carbon fiber	In progress
9	Piasecka&Żylewicz	-	team skills development	In progress
10	Weil	-	legal support	In progress
11	GMV	MA, ADCS	simulations	In progress
12	Sener	DT, TCS	experience sharing	In progress
	LTT	SunS	rent a lamp for Sun Sensor tests	Suspended
	Rapid Crafting	DT, SunS, PR	3D printing	Suspended
	Antmicro	OBC	software	Suspended
	SSBV	SunS	components providing	Suspended
	Creotech Instruments	OBC, CAM	components providing, services, experience	Finished

Appendix B TEAM SUPERVISORS

Table B-2 List of PW-Sat2 team supervisors as of August 2016

Team	Description	Team Leader	PW Supervisor	CBK/CAMK Supervisor	Other
ADCS	Attitude Determination and Control System	Inna Uwarowa (MEiL)	dr inż. M. Zasuwa (Zakład Automatyki i Osprzętu Lotniczego, MEiL)	mgr inż. Grzegorz Juchnikowski (Laboratorium Konstrukcji Elektronicznych)	Arthur Overlack (ISIS) Paweł Jaworski
CAM	Cameras	Mateusz Sobiecki (MECH)			
COMM&GS	Communication & Ground Station	Kamil Sażyński (EiTI)	dr inż. Krzysztof Kurek (Instytut Radioelektroniki, EiTI)		mgr inż. Tomasz Rybarski
CONF	Configuration	Paweł Brunne (MEiL)			
DT	Deployment Structures	Ewelina Ryszawa (MEiL)	dr inż. Zbigniew Kusznierewicz (Instytut Mikromechaniki i Fotoniki, Mechatronika) prof. dr hab. inż. Włodzimierz Kurnik (Zakład Mechaniki, SiMR PW)		Sener
EPS	Electrical Power System	Piotr Kuligowski (EiTI)			Sławosz Uznański, PhD (CERN)

Team	Description	Team Leader	PW Supervisor	CBK/CAMK Supervisor	Other
MA	Mission Analysis	Artur Łukasik (MEiL)		mgr inż. Elżbieta Zocłońska (CAMK)	GMV
OBC	On-Board Computer	Daniel Dec (FP)			Future Processing, Grzegorz Gajoch (Airbus Defence and Space)
OPER	Operation	Dominik Roszkowski (MEiL, MiNI)			Softwaremill
PR	Public Relations	Dominik Roszkowski (MEiL, MiNI)			Marcin Świetlik (PW) Jarosław Kacprzak (Future Processing)
SunS	Sun Sensor	Mateusz Sobiecki (MECH)	dr inż. Stanisław M. Pietruszko (Instytut Mikroelektroniki i Optoelektroniki, EiTI)	dr inż. Mirosław Rataj (Laboratorium Fotoniki i Mikromechaniki)	
TCS	Thermal Control System	Alan Budzyński (MEiL)			mgr inż. Michał Szwajewski (Sener)