STUDENTS' SPACE ASSOCIATION

THE FACULTY OF POWER AND AERONAUTICAL ENGINEERING
WARSAW UNIVERSITY OF TECHNOLOGY

PW-SAT2

PRELIMINARY REQUIREMENTS REVIEW

Phase A of PW-Sat2 project

1.2 EN

pw-sat.pl

2014-08-06

Abstract

The following paper is an introduction to Phase A Summary of student satellite project PW-Sat2. This part describes the organization of the team, the architecture of the system, the assumptions and tasks for the team. It also presents all proposed versions of the financial and mass budget, a description of working modes and the analysis of possible unwelcome events.

Revisions

Version	Date	Changes	Responsible
1.0	2014-04-07	Final version of this document in Polish.	Dominik Roszkowski Inna Uwarowa
1.0	2014-05-08	English version of this document.	Dominik Roszkowski Inna Uwarowa Alan Budzyński
1.1	2014-08-06	New system architecture, new EPS architecture, added requirements for OBC.	Piotr Kuligowski
1.2	2017-03-21	Disclaimer added – out of date doc	Dominik Roszkowski

Attention Phase A documentation may be outdated in many points. Please do not depend on Phase B or Phase A documents only. Current documentation is available on the project website pw-sat.pl

The Preliminary Requirements Review consist of:

1. This very introduction

And descriptions of the following subsystems:

2. Thermal Control System [TCS]
3. On-board computer [OBC]
4. Electrical Power System [EPS]
5. Attitude Determination and Control System [ADCS]
6. Communication [COMM]
7. Deployment Team [DT]
8. Cameras [CAM]
9. Sun Sensor [SunS]
10. Mission Analysis [MA]

All these documents are also available in Polish.

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1 PROJECT ORGANIZATION

1.1 BEGINNINGS

The PW-Sat2 project started in January 2013, about one year after the preceding PW-Sat launch. First meetings and workshop were focused mainly on choosing a reasonable selection of experiments to include on the satellite and developing a schedule of the project. The team of students decided upon two priority payloads – a Deorbitation System (Deployable Sail) and a Sun Sensor. Later we resolved to have – at first one – and then two cameras on board as well; CAM1 pointing at Earth and CAM2 to record a deployment of the sail. We also decided to develop deployable solar panels to improve energy efficiency and the reliability of PW-Sat2. Subsequent meetings allowed us to analyse and choose the optimal solutions and investigate whether our ideas are possible to realize.

1.2 MISSION PLAN

1.2.1 PHASE 0

In the phase 0 the following payload had been defined, according to the highest priority:

1. Deorbitation system – 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

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

1.2.2 PHASE A

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 behaviour in dynamically changing temperature. Ultimately it was decided to use flat springs instead. The first prototypes are promising and demonstrate high reliability of the system. A detailed description can be found in the DT phase A documentation, which is included with this document.
2. Sun sensor – 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 which is included with this document.
3. Solar Arrays Deployment System – during 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 which is included with this document.
4. Cameras:
    a. CAM1 – after a detailed mission analysis it was decided to forfeit the camera planned for Earth pictures. Main reasons of the decision: 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 deorbitation 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 which is included with this document.

Basic systems [summary included]

1. On-board Computer (OBC) [3] – quasi redundant,
2. Electrical Power System (EPS) [4] - redundant,
3. Thermal Control System (TCS) - passive,
4. Communication System (COMM) [6] – 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.

5. Attitude Determination and Control System (ADCS) [5] – active, magnetic.

1.3 ORGANIZATION STRUCTURE

The PW-Sat2 project organization is assuming a greater cooperation with the University. The main project structure is presented in the diagram below (Figure 1-1).

PW-Sat2 has its project manager and vice project manager, both students, who are obliged to report to the university main project supervisor. 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 centre or company, and supports the team with his or her knowledge in the field related to the team's focus. It is important to have a person who can evaluate our work and judge it in a professional way. It is hard to find any one person who possesses detailed knowledge about all of the subjects connected with the satellite project; mechanics, electronics, software, thermal analysis etc. Taking this into account there were chosen three supervisors for the EPS, OBC and COMM teams, divided into software, hardware and radio communication profiles. It should be noted that the team advisor is a person who already finished his studies, but doesn't necessarily have much experience as a supervisor. The advisor is a person with which the team members can contact directly in any case.

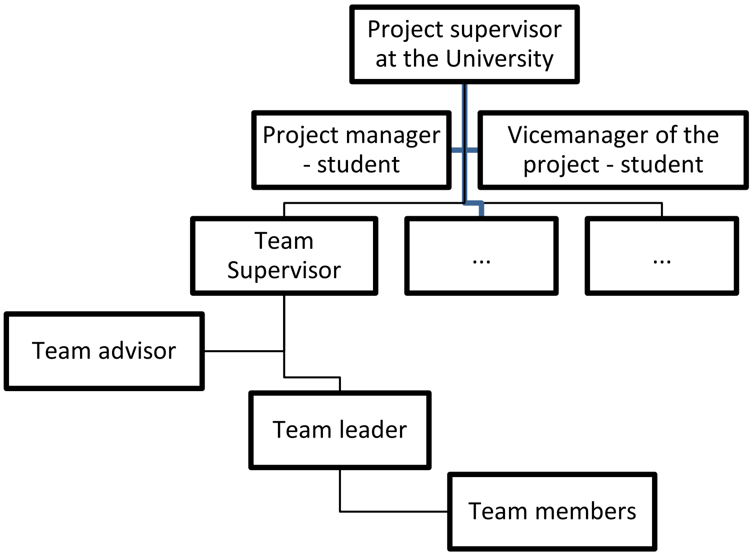


Figure 1-1 Scheme of the organization structure of the PW-Sat2 project

The project is gaining interest of companies from the space sector, which are ready to provide the substantive support for the team in technical issues. We believe that in the future they will also be ready to provide financial support, in form of real system components or software.

Specific information about the project supervisors and advisors can be found in the end of this document [Appendix 1]. In phase 0 of the project, all members were one common group. At the beginning of phase A it was identified a need to divide the members into teams. Currently, 11 teams are working on the project. Most of them correspond to the satellite subsystems.

The DT team will emerge during phase B as the new Configuration Team (CONF). The team will be responsible for configuration of the satellite, i.e. an optimal arrangement of all the subsystems according to their requirements.

The same will happen in the case of the MA. During phase B, the Operation Team (OPER) will be formed, which will be involved in the satellite control after its launch. However, before launching the satellite, members will learn to control, develop telecommands and telemetry format with a team of OBC and COMM. The plans also include training and an exam for the radio amateur licence.

During phase A the GS team was established, which had to work with the construction of a new ground station, or the improvement of an existing one. During the work it was determined that there is no real need for building a new ground station. The cooperation with existing stations have been arranged, where they have agreed to participate in communication with the satellite after launch. Eventually it was decided that the GS team will report directly to the communications team.

The short descriptions of the existing teams are presented below. The full list of teams with names of their team leaders is included in the [Appendix 1].

ADCS	Team responsible for the ADCS module (magnetometers, magnetorques, attitude control realization, control algorithms)
CAM	Team responsible for the Cam1 (pointing at Earth) and Cam2 (pointing at sail) (camera1, camera2, components, data handing)
COMM	Team responsible for the communication module (antennas, communication module, frequency allocation, telemetry, telecommands)
DT	Team responsible for the deorbitation structure and solar arrays deployment system (deorbitation system design, testing and manufacturing)
EPS	Team responsible for the EPS module (batteries, solar cells, power budget, EPS module, power scenarios)
GS	Team responsible for the Ground Station (Ground Station organization)
MA	Team responsible for Mission Analysis (satellite dynamics simulations, launch opportunities)
OBC	Team responsible for the on-board computer/OBC (data handing <OBDH>, OBC module, software)
PR	Team responsible for public relations and project promotion
SunS	Team responsible for the Sun sensor experiment organization (Sun Sensor testing stand, Sun Sensor manufacturing)
TCS	Team responsible for the thermal control system (system design, MLI, thermal models)

Table 1-1 Descriptions of the PW-Sat2 teams

1.4 TEAM MEMBERS

At the beginning, in January 2013, the project numbered 28 people and since then 18 of them have left or suspended their activity. In November, after the recruitment process, 29 new members have joined the PW-Sat2 team. In March 2014 there are 39 people divided into 10 teams. The [Appendix 1] presents the number of members in each team.

2 SYSTEM ARCHITECTURE

In this chapter the following information about PW-Sat2 systems are presented:

- flowchart of all electrical connections between subsystems and sensors,
- subsystems chosen to buy,
- description of requirements for subsystems, which will be built by our team,
- proposed flowcharts of subsystems that will be built.

2.1 PW-SAT2 SUBSYSTEMS

The main task of PW-Sat2 satellite is to test a deorbitation system. The system works on the principle of increasing aerodynamic resistance. In a low orbit there is a residual atmosphere that will allow the system to work properly. Because of increasing aerodynamic resistance the orbit will lower and after some time it will lead to entrance to lower parts of the atmosphere and burn out.

Second task is a test of Sun Sensor, including 4 small solar cells. Every cell produces a current that is measured. A position of sun is calculated on a base of the value of current and arrays saved in microcontroller's FLASH memory.

The next task is taking a picture of the Earth from the orbit and registering a moment of releasing a deorbitation structure by the CAM2 camera (VGA resolution).

Power Supply System is receiving energy from solar cells, stores it in accumulators, manages power switches and reacts in case of emergency. Power switches are controlled from the on-board computer.

All the systems are managed by the on-board computer. It processes commands received from the Earth, monitors power budget, receives data from cameras and automatically executes tasks from built-in schedule.

Communication module allows to communicate bidirectionally with ground station – to send commands and receive data. It uses UHF/VHF.

ADCS stands for Attitude Determination and Control Subsystem. An active magnetic system allows us to change orientation of the satellite in a limited scope.

2.2 Flowchart of the system

See [Appendix 2 Flowchart of the PW-Sat2 systems].

2.3 Communications module COMM1

Communication module VHF downlink and UHF uplink is responsible for receiving commands, sending telemetric and payload data. Modules taken into consideration:

Name of the module	Power consumption – receiving	Power consumption – transmitting	Supply voltage	Bitrate
ISIS VHF downlink / UHF uplink Full Duplex Transceiver	<0,2W	<1,7W	6,5V – 12,5V	Transmitting to 9,6kbps Receiving to 1,2kbps
ISIS UHF downlink / VHF uplink Full Duplex Transceiver	<0,35W	<2,0W	5V – 18V	Transmitting to 9,6kpbs Receiving to 1,2kbps
ClydeSpace UTRX; Half Duplex UHF Transceiver	<0,25W	4W – 10W	6V – 9V	Up to 9,6kbps
GOMSpace NanoCom U482C	0,17W	1W – 3,7W	3,3V	Transmitting to 9,6kbps Receiving to 4,8kbps

The ISIS VHF downlink / UHF uplink Full Duplex Transceiver from www.cubesatshop.com was chosen:

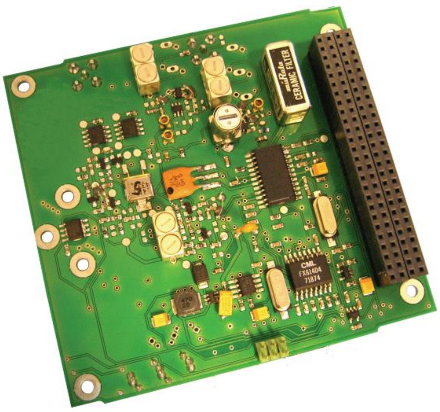


Figure 2-1 ISIS VHF downlink / UHF uplink Full Duplex Transceiver

The module is connected to system I2C bus. Power consumption while transmitting is specified up to 2W, while receiving 200mW. Power of transmitter is 22dBm, sensitivity of the receiver is -

104dBm with BER 10E-5. Supply voltage is 6.5-12.5, so the module can be supplied directly from 2 Li-ion accumulators package connected in series. A connection between a module and antennas is realized by using coaxial cables.

Most of the time the module must work in receiving mode. Despite the fact, that this is a module for commercial use, we should execute very accurate tests in vacuum chamber in order to prevent the module to overheat.

2.4 ANTENNA MODULE ANT1

Module with decomposing antennas UHF/VHF. We've chosen ISIS Deployable Antenna System from www.cubesatshop.com:

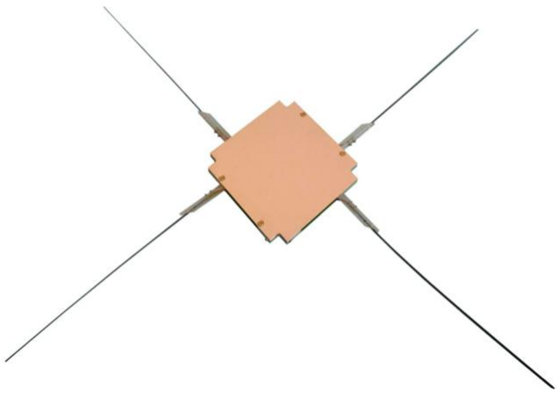


Figure 2-2 ISIS Deployable Antenna

It is a pair of 2 folded dipole antennas – one from VHF one from UHF. The module contains 2 redundant microcontrollers controlling thermal knives that burn out a Dyneema cord. A burn out order is received from I2C bus. During burning out the module is taking about 2W of power. After burnout antennas deploy, and send a confirmation if succeeded. A RF signal is supplied by SSMCX connectors and by coaxial cables. Loss from input to antennas is 1.5dB.

The module will be connected directly with EPS, in order to minimize a number of active subsystems during intro-sequence after releasing from P-POD. A connection with EPS is realized by 9-pinned connector shown below:

Connector	Pin	Name	Level	Remarks
J1	1	Vcc	3.3V nominal (min 3.0V, max 3.6V)	Positive supply voltage
	2	SDA_A	0-3.3V nominal (5V tolerant)	I2C data A
	3	GND		Ground
	4	SDA_B	0-3.3V nominal (5V tolerant)	I2C data B
	5	GND		Ground
	6	Vcc	3.3V nominal (min 3.0V, max 3.6V)	Positive Supply Voltage
	7	SCL_A	0-3.3V nominal (5V tolerant)	I2C clock A
	8	SCL_B	0-3.3V nominal (5V tolerant)	I2C clock B
	9	GND		Ground

An I^2C bus will be connected to the internal system bus. 3.3V supply will be turned on independently from EPS system.

2.5 ELECTRICAL POWER SYSTEM EPS

Supply system will be designed and assembled by PW-SAT2 team. It will be receiving energy from solar cells, storing it in accumulators, converting voltages to supply different subsystems and distributing it. The module has to provide the execution of basic task – deploying deorbitation structure, even if a major failure with any subsystem or EPS will appear.

2.5.1 DETAILED REQUIREMENTS FOR EPS

a) Possibility of connection of 6 solar panels distributed as shown below:

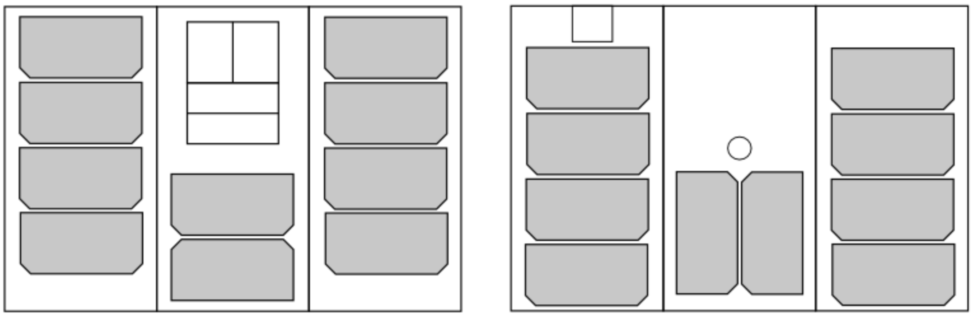


Figure 2-3 Scheme of solar panels distribution - views from the top and from the bottom

On every surface the solar cells are connected in series. There will be 3-junction cells with efficiency about 30%. Maximal theoretical power from each of the cells is 1W. Maximal power of 1 panel containing 4 cells is 4W. Maximal voltage on a panel, containing 4 cells is about 10V. Maximal current is 0.5A. We expect 4 panels containing 4 cells each (wings) and 2 panels containing 2 cells each.

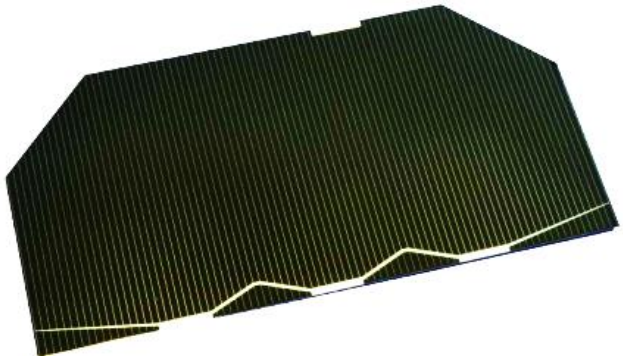


Figure 2-4 Solar cell AzurSpace with dimensions 80x40mm and efficiency 30%

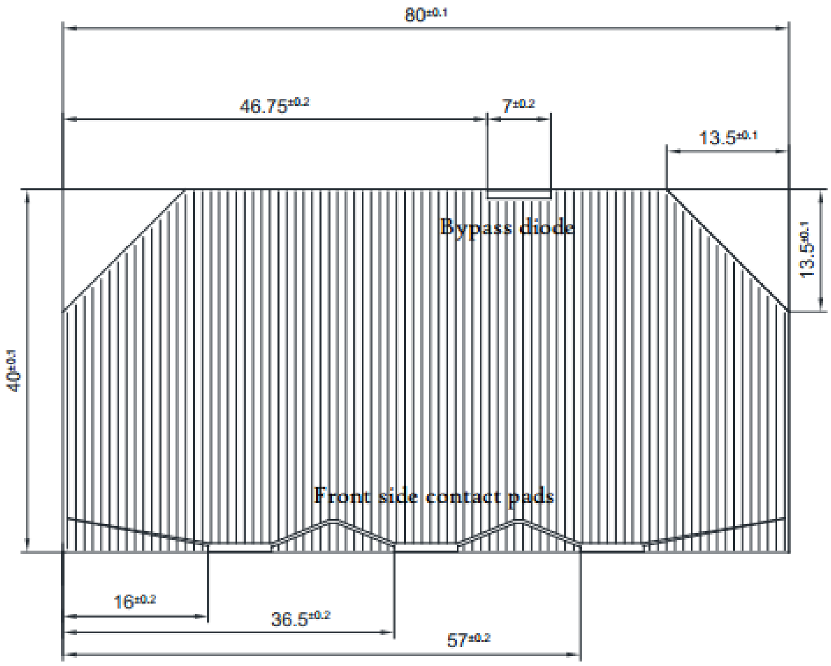


Figure 2-5 Dimensions of the AzurSpace solar cell

b) Tracking of maximal point of power MPPT of each surface of solar panels. System should have its maximal possible power, which will be achieved by using pulse converters controlled by microcontroller. In one moment only 3 surfaces can be lighten up, so one can limit the number of pulse converters to 3. To every one of them should be connected opposite-sided panels.

c) Redundancy of basic, critical sections of power system. For example: charger modules and accumulators modules can be redundant (2 independent chargers with 2 independent accumulator packages), or redundant pulse converters for supplying different subsystems.

d) Possibility of supplying subsystems directly from solar panels, without accumulators. There must be such a solution, because it will allow executing a mission even if the accumulators were damaged.

e) Possibility of manually disconnection of accumulators using RBL (switches turned on just before start) and deactivate system by kill-switches (separative switches).

f) Creating voltages 3.3V, 5V and possibility for supplying directly from accumulator package. Required voltages and maximal power consumptions for each subsystem are listed below:

Abbreviation	Full name	Supply	Power consumption
COMM1	Transceiver VHF/UHF	6.5-9V	Transmitting: <2W Receiving: <0.2W
ANT1	Deployable antennas VHF/UHF	3.3V	While deploying antennas: 2W up to 30s After deploy: 0W (cut-off)
BATTERY	Accumulator package	Accumulator	Heating: 1W in shadow zone
EPS	Supply system	Internal	Sleep mode: <0,1W
SADS	Solar Array Deployment System	6.5-9V	Opening of the panels: 2W up to 30s
Sail	Sail – deorbitation system	6.5-9V	Opening of the deorbitation structure: 2W up to 30s
ADCS	Attitude Determination and Control System – actuator modules with PWM drivers	3.3V 5V	Supply for sensors and electronics: <0.5W Actuators supply: <1.5W
PLD	Payload electronics	5V 3.3V 6.5-9V	SunS: 1W Photodiodes: 0.5W TCS: max 1W
OBC	On-board Computer + Magnetometer + CAM2	6.5-9V	OBC processing: <1.5W OBC low-processing-load: <0.5W OBC sleep-mode: <0.1W CAM2: <1W (1.5W+1 W = max 2.5W)

Table 2-1 Required voltages and maximal power consumptions for each subsystem

The largest load of EPS occurs while changing orientation with turned on main camera and heater. Together with maintaining basic functionalities of satellite a load could increase up to 10.5W in peak (bus 3.3V – 3W, bus 5V – 2.5W and bus 6.5V – 9V to 5W). Algorithms of power management should prevent from such situations, but when designing EPS we should consider situations like this. In a table below there is summed power consumption from different power buses:

Power bus	Summed power from all subsystems on a bus
3.3V	2.5W while 30s (deploying ANT1) 5W other subsystems
5V	3W – continuous power
6.5V-9V	2*2W during 30s (opening panels and sail) 6.5W other subsystems

Table 2-2 Maximum power consumption from different power buses

Current requirements for power buses (based on table above):

Power bus	Required actual/ continuous current
3.3V	3A – maximal during 30s (together with deploying system of ANT1) 2A – continuous current
5V	0.8A – continuous current
6.5-9V	2A – maximal during 30s (opening sail and solar panels and working subsystems on the same moment – not possible, but EPS must survive it) 1A – continuous current

Table 2-3 Current requirements of power buses

A table above that contains maximal currents is rather an approximation and a general view on the problem. In the real circuit actual values of current will not be reached (the average current will not be larger than half of the values presented in the table above). However, the values above will be considered while designing converters and circuits around them.

g) Possibility of supply disconnection for every subsystem will allow saving more energy. Keys (electronic switches) turning on supply voltage should be located on buses 3.3, 5V and 6.5-9V. Every one of them should have over-current protection and has to be controlled from OBC. Communication module COMM1 and OBC may be disconnected only when an emergency situation appears, so they have to have their own hardware protection.

h) Execution of main task – deploying deorbitation structure – in spite of failure every other subsystems of satellite, even supply. To make this possible, there should be a time module which will measure the time from deploying deorbitation structure. The module should be independent from other parts of EPS and cannot be supplied from pulse converters. It imposes necessity of adding security modules connected directly to solar panels with its own real time clock. When it measures established time it would execute deorbitation procedure. Time counting should not stop in shadow zone.

i) Emergency disconnection of subsystems from accumulators when deep discharge. The module should warn OBC before disconnecting in order to allow saving latest work results.

j) Running in space: vacuum (without convection – problems with cooling), high temperature tolerance (-40 to 60°C), tolerance for damage of single integrated circuit by radiation.

k) Protection against accumulators explosion (e.g. because of improper degassing).

l) Protection against damaging single pulse converters of chargers or supplying subsystems.

m) Monitoring of currents and voltages of supply buses, accumulators and solar panels power. Temperature measurements.

o) Monitoring the state of OBC and when it's damaged switching to reserve one.

p) Communication with OBC through system bus.

Abbreviation	Supply bus	No. of keys and maximal current	Placement of a key
COMM1	6.5-9V	1st key: 400mA	EPS
ANT1	3.3V	1st key: 610mA during 30s 6,1mA after opening of antennas	EPS
BATTERY	Accumulator	1st key: heater - key and thermostat included in accumulator package module	BATTERY
EPS	Internal	-	-
SADS	6.5-9V	1st key: 400mA during 30s	EPS
Sail	6.5-9V	1st key: 400mA during 30s	EPS
ADCS	3.3V 5V	1st key: 200mA 2nd key: 300mA	EPS EPS
Payload electronics PLD	3.3V	1st key Photodiodes: 300mA	EPS
	5V	2nd key SunS: 200mA	EPS
	6.5-9V	3rd key TCS camera: 600mA	EPS
OBC	6.5-9V	1st main key OBC: 500mA	EPS

Table 2-4 Required supply keys for various elements

Supply voltage	Supply bus	To subsystem	Maximal key current
3.3V	Direct connection	ANT1	610mA during 30s
	Main bus	ADCS	200mA
	Main bus	PLD	300mA
5V	Main bus	ADCS	300mA
	Main bus	PLD	200mA
6.5-9V	Main bus	COMM1	400mA
	Direct connection	SADS	400mA during 30s
	Direct connection	Sail	400mA during 30s
	Main bus	PLD	320mA
	Main bus	OBC	500mA

Table 2-5 Triggering keys – by supply bus order

2.5.2 Flowchart of Electrical Power System

See [Appendix 3 Flowchart of Electrical Power System].

2.6 Accumulators package

Accumulators package include accumulators and thermostat with heaters. The heaters will allow accumulators to work while being in shadow zone. Accumulator package with certificate should be bought, in order to have it tested in vacuum chambers. We've chosen GOMSpace NanoPower BP4:

Figure 2-6 GOMSpace NanoPower BP4

To increase reliability of EPS and protect single accumulators from damage, there must be at least 2 independent charger modules. According to reseller information, there is a possibility of connecting accumulators in the order : 2 packages including 2 accumulators each.

Capacity of accumulators is about 40Wh. With discharge coefficient DOD 25%, accumulator capacity decreases to 80% after about 1700 cycles of charging-discharging. To increase battery life we should keep discharge coefficient relatively low and charge to 70% of capacity (so that the accumulator package will remain 8000 cycles).

Every accumulator contains its own heater:

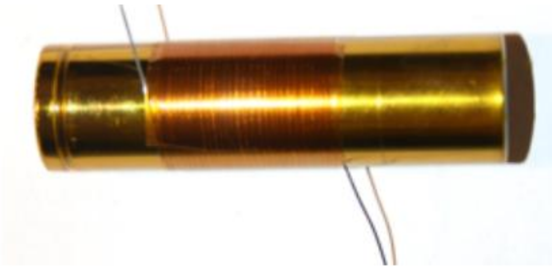


Figure 2-7 GomSpace 18650 battery with heater element

2.7 ADCS

System changes orientation of satellites. On the board of the subsystems there are actuators (executive elements –magnetorques), PWM actuator controllers and temperature sensors. We’ve chosen ISISMagnetorquer Board from www.cubesatshop.com:

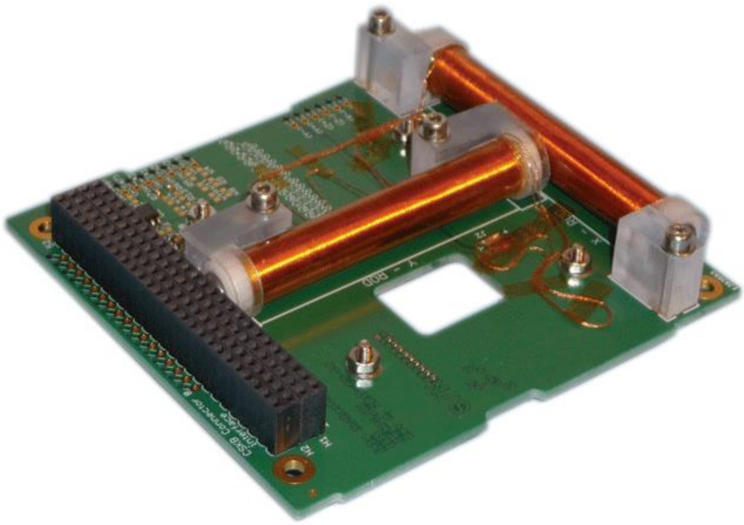


Figure 2-8 ISIS Magnetorquer Board

The subsystem is controlled via I²C bus. Algorithms controlling ADCS is located in OBC, which reads orientation data from sensors(SunS, photodiodes magnetometers, gyroscope) and gives commands to ADCS actuators.

Actuators are supplied 5V, sensors and logic 3.3V. ADCS requires OBC to work. In case of OBC failure, reserve microcontroller should be able to execute basic functions such as: detumbling or Sun-tracking.

2.8 PAYLOAD ELECTRONICS (PLD)

Electronics of the payload will be designed by team PW-Sat2. It includes electronics of: sun sensor, photodiodes, cameras and thermal control subsystem.

2.8.1 SUN SENSOR (SUNS)

The main task of sun sensor electronics is measurement of temperatures and currents of each cell. Cells should be polarized by voltage of a minimum 5V to have linear dependence between current and luminance (current of a cell polarized 0.5V). Polarizing cells takes much power and causes in cells warming up. That's why polarization should be connected only when a measurement is made. While processing the data it should be disconnected.

The position of Sun is determined on a basis of comparisons of currents and arrays inside memory. According to numerical simulations, the tables have a size about 6MB, so minimal size of memory should be 8MB. It requires adding external Flash memory. While computing the data the temperature of cells should be considered. ADCS sends to OBC position of the Sun in 2 angles via payload I^2C bus.

2.8.2 Flowchart of the Sun Sensor system

See [Appendix 4 Flowchart of the SunS system].

2.8.3 Photodiodes

The main reason of installing photodiodes is determining an approximate position to the Sun. They will be located on walls of the satellite. ADCS subsystem can use them to track the Sun or set a position while other sensors failure. Expected accuracy is couple degrees.

The electronics of payload measures the current flowing through the reverse polarized photodiodes. If on every one of walls the photodiodes will be close to each other, there will be a possibility to locate temperature sensor to make data processing more correct (photodiodes temperature consideration in algorithm). To the measurement ADC converter is required. There will be ADC converter connected to payload I^2C bus.

2.8.4 Camera's electronics

Electronics of cameras includes supply modules (stabilizers), if camera requires special supply voltages (e.g. 2.5V, 1.8V), which is turned on from OBC by command.

2.8.5 Thermal control system for the Camera

Camera thermal control system is turned on just a moment before turning on a camera, to heat it up to required working temperature. It includes thermometers and analogue thermostats (comparators). Heaters are turned on by transistor switches. If a camera is not supplied, camera thermal control system keeps it temperature above minimal temperature of storing. Power of heaters will be determined on a basis of thermal simulations by TCS team.

2.9 CAM2 camera

The main task of CAM2 is recording a low resolution video showing deorbitation structure deployment and taking some photos of VGA resolution. Camera will be compressing pictures and send it to OBC via OBC electronics.

Camera used in prototype CAM2:

Size of CCD matrix: 1/6", resolution: 640x480, power consumption: 300mW, frames per second: up to 30, dimensions: 6x6x4.5mm, interface I^2C, format: YUV422, RGB565, weight: 1g, view angle: 45^0

The camera requires thermal control system - thermometer and heater. Before turning on a camera a temperature will be checked. When the temperature is too low the camera won't be turned on.

2.9.1 DETAILED REQUIREMENTS FOR CAM2

a) CAM2 mass must be less than 150g.

b) Power consumption must be less than 1W (power switch on OBC board).

c) Max. height over OBC-PCB must be less than 40mm (PLD-PCB is over OBC-PCB. On PLD-PCB can be cut a hole).

d) Integrated heaters and temperature sensor (connected to TCS on PLD board).

e) Wide-angle lenses for wide angle of view (min. 90 degree).

f) CAM2 must have on view a part of deorbitation-sail.

2.10 ON-BOARD COMPUTER

A task of PW-Sat2 team is designing and building OBC – one board with dimensions of PC-104 standard. Module will be working in cosmic space conditions - vacuum witch very big temperature gradients (from -40°C to 60°C) and increased ionizing radiation.

2.10.1 DETAILED REQUIREMENTS FOR OBC

a) Communications via I^2C with other subsystems of satellite. System and payload (experiment) bus are separated.

b) Time measurements of mission duration after throwing out from P-POD and power switching. Clock which counts time should run in spite of temporary black outs. State of a timer should be saved in couple of different memories from time to time, but not so often to avoid destroying the memories.

c) Executing scheduled tasks – build-in list of tasks to realize during a mission.

d) Possibility of executing every task sent from the Earth before scheduled time saved in schedule list.

e) Executing simple scripts sent from Earth.

f) Monitoring of power budget and sending commands to EPS, that turns on/off supply keys.

g) Receiving data from camera. Camera (CAM2) sends compressed series of photos in VGA resolution (2-5 frames per second). Received data has to be saved in Flash memory.

h) Handling parallel NOR Flash memory for image data, SRAM memory minimum 1MB (operational memory) and small block of FRAM memory (integrated ferrite memory to store critical configurations and map of destroyed cells of operational memory).

i) Computer must be supervised by hardware watchdog.

j) Hardware reset system must be connected to the reset line

k) Computer reset after determined time will avoid long-term software bugs to propagate.

l) Possibility to substitute the main computer with reserve microcontroller.

m) On a main board, connections to external magnetometers must be provided, so a key that turns on/off its supply and I2C or SPI bus is required.

n) Provided place for MEMS gyroscope with filters on board.

o) Computing power big enough to handle data from cameras.

p) OBC will compute position and appropriate actuator positions. Reserve computer must be able to execute basic tasks: detumbling and sun tracking.

r) Mechanical and electrical compatibility with PC-104 standard for Cubesats (Samtec stackthrough connector ESQ-126-39-G-D).

3 MASS BUDGET

Three cases of PW-Sat2 configuration were prepared as shown in the table below [Table 3-1]:

11. Configuration containing all subsystems [rejected at the day of publication]
12. Satellite without CAM1 and S-band antenna
13. Case 1 with additional reference Sun-sensor

				Max.	Min.	Max.	Min.	Max.	Min.
				Case 0		Case 1		Case 2	
Team		Components		Mass [g]		Mass [g]		Mass [g]	
BUS	OBC	Hardware		100	100	100	100	100	100
	EPS	EPS module		100	90	100	90	100	90
		Solar panels (23 pc)		383	383	383	383	383	383
		Batteries (2 bundles)		240	240	240	240	240	240
	COMM	S-Band antenna		85,90	85,90				
		S-Band module		62	62				
		UHF/VHF module		85	85	85	85	85	85
		UHF/VHF antenna		100	100	100	100	100	100
	ADCS	Magnetourqers		195	195	195	195	195	195
		Magnetometer		5	5	5	5	5	5
		Sun sensor		0	0	0	0	5	5
		Photodiodes		3	3	3	3	3	3
	Struct	Structure		140	140	140	140	140	140
Payload	DT	Sail	Casing and sail	700	400	700	400	700	400
		SADS	Machinery and springs	120	70	120	70	120	70
	SunS	Sun sensor		100	70	100	70	100	70
	CAM	CAM1		60	40				
		CAM2		40	20	40	20	40	20
	Payload electronics			100	70	100	70	100	70
Other	Cables			160	160	135	135	160	160
	MLI			25	20	25	20	25	20
Sum				2803,90	2338,90	2571	2126	2601,00	2156,00

Table 3-1 Set of proposed mass budgets

4 FINANCIAL BUDGET CASES

4.1 CASE 1

Case 1 assumes 19 solar panels and full version of control system. This version excludes CAM1, S-band antenna module and S-band communication module.

In the table below elements that shall be bought from external companies were shown.

Commercial elements:	Comments
Solar Panels 19 pc	19 panels * 300€ + assembling 3000€
Batteries	Manufacturer: GomSpace
Communication module	ISIS
Antenna module	ISIS
ADCS: board with electromagnetic coils + photodiodes + magnetometer + gyroscope	ISIS board 7500€ + magnetometer $80 + gyroscope $25 + photodiodes 36€
Camera CAM2	Sum contains manufacturing of electronics and test versions

Table 4-1 Elements bought from external companies

4.2 CASE 2

Contains additional sun sensor in comparison to Case 1, which shall be a reference sensor used as a payload SunS. It will allow verification of accuracy of the tested sun sensor. Commercial sensor offered by ISIS company.

4.2.1 DETAILED CASES

Both cases can be found in the enclosure:

1. Appendix 5 Case 1 of financial budget of PW-Sat2 project
2. Appendix 6 Case 2 of financial budget of PW-Sat2 project

5 WORK MODES OF THE SATELLITE

Below the basic work modes and tasks done by the main computer of the PW-Sat2 satellite are described.

1. DETUMBLING

After the ejection of the satellite from the P-POD the electric circuit is being closed and EPS executes first run of the OBC. First task is to check the basic parameters of all subsystems and to determine the spin of the satellite. In case of need to stop the tumbling of the satellite, ADCS will be set into the DETUMBLING MODE. At the same time, data will be recorded and sent to the Earth for further analysis of the condition of the satellite during phase 1. After detumbling satellite will open UHF/VHF antennas and will be set into SAFE MODE.

2. SAFE MODE

During this mode the satellite tries to set itself in the most efficient position in order to maximize the Sun energy. At the beginning the Solar Arrays are folded, so initially only one of the sides is fully illuminated. The Communication (COMM) system is being turned on in receiving mode. In case of no signals received next scheduled tasks are executed.

3. BASIC TELEMETRY COMMUNICATION SESSION

When the satellite will receive signals from the ground station, it will start sending back the basic pack of telemetric data until receiving the command to stop this task. In order to provide the effectiveness of the ADCS, it is necessary to send actual TLE data back to the satellite.

4. 1ST COMMISSIONING

At request of the ground station, satellite sends data packages obtained during phase 1 realization (see point 1) – since the ejection from P-POD till the end of detumbling.

5. SADS OPENING

After receiving one-time command the solar panels are deployed. Since this moment, assuming correct operation of the system, satellite being in SAFE mode is able to face the Sun with all 3 walls. In case of lack of communication with Earth the task will be performed automatically after specified time or by decision made by OBC due to the low energy balance, if ADCS is fully operational.

6. Photo downlink

After receiving the command to upload pictures and movies, the satellite sends specified data if there is enough energy to perform this action – which is stated before.

7. SunS calibration

A command executing calibration of the experimental sun sensor and causes the satellite to face to the Sun with the wall at which the sensor is mounted to. Maximal signals are detected on the sensor cells meaning that since this moment SunS will be able to indicate the direction of solar rays incidence using satellite coordinates.

8. SunS tests

SunS test mode requires specified spin of the satellite from ADCS in order to perform tests. It can be performed also using natural spin of the satellite.

9. SAIL deployment

A command executing start-up of the deployment mechanism of the SAIL, a turn-on of CAM2 camera in order to register the process of SAIL deployment. In case of lack of this command before the specified time, this task will be performed automatically.

See also the ADCS working modes in ADCS document.

6 ANALYSIS OF POSSIBLE UNWANTED EVENTS DURING MISSION OF THE PW-SAT2

6.1 INTRODUCTION

Under risk analysis conducted for PW-Sat2 satellite project – during phase 0 – simplified method based on FMEA (*Failure Modes and Effects Analysis*)[1] was used. As a result, only 4 unwanted events (from 207 identified possibilities) leading to mission failure were selected, for which the risk was the highest:

1. EPS failure
2. TCS failure
3. Communication system failure
4. Software errors

Due to the preliminary stage of project at which the analysis was conducted, identified unwanted events are only at very general level.

6.2 INFLUENCE OF PHASE 0 RISK ANALYSIS ON PROJECT AT PHASE A

In order to decrease the risk connected with listed unwanted events during phase A, a set of solutions were applied:

6.2.1 EPS FAILURE

In case of EPS, high requirements concerning its reliability were set. Its failure may lead to the failure of the whole mission. In order to prevent this, proper safety actions were applied. First of all, redundancy of basic EPS blocks: accumulators bundles, chargers, converters following maximal power point and controllers. Hardware and software protections control EPS work in real time. Independent timer counts time until activation of deorbitation system and even in case of EPS damage it still continues mission.

[1] See. Łukasik A., *Satellite reliability analysis – Intermediate Engineering Project*, Warsaw University of Technology, The Faculty of Power and Aeronautical Engineering, Warsaw 2013

High number of charging cycles leads to fast accumulators usage. In order to decrease this effect depth of discharge coefficient was limited.

A series of tests with use of stratospheric balloon will allow detecting errors connected with system overheating, and long-term tests will allow detecting software errors. Support of scientific staff from Warsaw University of Technology and other companies allows to avoid basic mistakes.

In power supply documentation selection of EPS architecture was presented. Accumulators were chosen and the most optimal depth of discharge coefficient was determined. Also, simulation of power balance was conducted and first prototype of converter following maximal power point of solar panels was made.

6.2.2 TCS FAILURE

Configuration and structure teams since the beginning of work cooperate closely with TCS team taking into account possible problems connected with thermal balance. Initial thermal analyses were conducted for the most probable PW-Sat2 orbits, for two cases: hot and cold case (only for structure and solar panels). Further, it will be necessary to conduct other, more detailed thermal analysis due to the developing model of the satellite, taking into account:

- configuration of internal subsystems
- maximal and minimal temperature limits for operation and survival limits for each subsystem
- amount of heat produced by each subsystem
- conduction of analysis with implementation of additional heaters and MLI sheets
- radiator optimisation
- design of effective thermal control system for electric components

Those analysis will be performed during phase B of the project and results will be taken into account in case of a satellite configuration. In future, results will be compared with physical thermal tests of the complete satellite.

Close cooperation of configuration and TCS teams, series of analysis and comparison of numerical results with physical one shall provide correct design and effective operation of PW-Sat2 thermal control system.

6.2.3 Communication system failure

In opinion of the PW-Sat2 team, deduced during risk analysis conducted in phase 0, risk connected with communication system failure is high. This opinion was influenced by few factors:

- problems with communication with previous satellite – PW-Sat,
- importance of communication system that it plays in proper satellite operation and its influence of mission success,
- insufficient amount of people in project having experience with communication system.

In order to decrease the risk connected with communication subsystem it was decided to take few steps:

- long-term tests of communication system are planned in laboratory conditions and with use of stratospheric balloon,
- realization of the main objective of PW-Sat2 mission – deployment of deorbitation sail is independent of communication with Earth, sail shall deploy automatically after certain time will pass,
- recruit new members to communication team,
- it was decided to buy a commercial communication system which shall decrease the amount of work of the team; only systems which were already checked in other space missions are considered to be bought.

6.2.4 Software errors

In order to minimize risk of errors in satellite software, it is planned to create a computer simulation for software tests. The objective is to verify the performance of OBC for as many cases as possible that may happen during mission. During next stage, long-term functionality tests of a complete satellite will be performed.

6.3 Risk analysis – Phase A

Due to few reasons at the end of phase A, it is recommended to perform again deeper risk analysis of the whole project:

- too general analysis performer during phase 0;
- many changes in project concept and satellite design;
- significant increase of members taking part in the project:
    - new people can have new ideas and comments;
    - new people usually have a very limited knowledge about the whole project (except the team they belong to) and interaction between teams. Taking part in risk analysis would be very informative and it would increase awareness of team members concerning influence of their decisions on the success of the whole mission;
- people taking part in the risk analysis during phase 0 obtained much higher experience and they are able to more accurately define risks of the project.

6.4 Initial risk recognition

The first stage of risk analysis (for phase A) was to initially recognize, by team coordinators, events that constitute the highest risk to mission success and their effects on other subsystems. Each subsystem was analysed separately which resulted in omitting their relations between each other during their work. Also, only technical aspects were considered without software risk. Additionally, negative effects of SAIL and solar panels deployment were taken into account.

6.4.1 Thermal Control System (TCS) failures

- battery heater failure
    - If the temperature of the battery will fall below its survival limit it will cause its damage and the satellite will be only operational when exposed to sunlight using power generated at solar panels instead of energy accumulated in battery
    - see. *EPS failure –permanent damage of all accumulators*
- accumulators temperature beyond operational limit, accumulators not damaged

  - When temperatures are beyond accumulators' operational limit, effects are similar to damaged battery. Those effects are reversed after return to operational temperature limits
- CAM2 survival temperature exceeding
  - possible permanent camera damage
  - no possibility to record SAIL deployment
- radiator facing the Sun during tumbling
  - majority of elements inside the satellite might get overheated
  - SAIL deployment system is independent of EPS and it is possible to continue its task even in case of EPS overheating
- high temperature gradient at the sun sensor wall
  - possibility of wall deformation causing change in shape of SunS and preventing further measurements

6.4.2 Electrical Power system (EPS) failure

- permanent damage of all accumulators
  - satellite will be able to operate only when exposed to sunlight using power generate at solar panels, instead of accumulated energy in battery;
  - due to the lack of power during eclipse, ADCS probably will not be able to stabilize orbit;
  - communication is set to listening mode;
  - rest of subsystems can operate in nominal conditions, taking into account limited amount of power;
- damage of one bundle of accumulators
  - faster discharge of remaining accumulators;
  - mission shall be as short as possible, no contradictions in other subsystems operation;

- half of EPS damage
  - It is necessary to reduce power consumption;

6.4.3 On-Board Computer (OBC) failure

- RAM damage
  - no possibility to record movies from camera;
- FLASH memory damage
  - loss of stored data; monitoring of damaged sectors and their exclusion from usage;
- FRAM damage
  - loss of actual settings, return to default setting;
- OBC main processor damage
  - switch-over to the second processor; disconnection of the camera;
- OBC both processors damage
  - acquisition of sail deployment task by EPS;
  - operation of EPS heater is independent of OBC;
  - rest of subsystems cease to function;

6.4.4 Attitude Determination and Control System (ADCS) failure

- total ADCS failure
  - no possibility of detumbling;
  - possibility of radiator facing to the Sun;
  - in case of high rotational speed, problems with communication might occur;
  - in case of high rotational speed, problems with sail deployment might occur;
  - no possibility to successfully direct solar panels to the Sun – lower power availability;
- magnetorquers and magnetometers failure
  - as above;
- photodiodes failure
  - decrease in orientation accuracy;

- no data from TLE
  - decreasing accuracy of orbit propagator anticipation, no information about position on the orbit in satellite computer;
- software errors
  - possible total failure of ADCS – see *total failure of ADCS*

6.4.5 Sail deployment (Sail) and solar panels deployment (SADS) systems failure

- Sail system failure
  - in case of incorrect deployment, sail can damage all external elements of the satellite – including solar cells and antennas;
- Sail deployment success
  - sail deployment significantly changes mechanical parameters of the satellite (moment of inertia, centre of gravity) and increases influence of aerodynamic drag force on satellite orientation, which causes work of ADCS more difficult;
  - deployment of sail based on long metal springs might interfere or prevent communication with Earth;
- SADS failure
  - change of assumed power budged, lack of power might occur;
  - deployment of only one solar panel might cause rotational motion of the satellite and influence moment of inertia of the satellite, complicating operation of ADCS;
- SADS successful activation
  - solar panels deployment causes change in centre of gravity and moment of inertia of the satellite and influence operation of ADCS;

6.4.6 Mechanical structure (CONF) failure

- too low stiffness of wall with mounted sun sensor
  - possible deformation of wall causing SunS shape change and preventing further measurements;
- incorrectly conducted tests on shaker
  - possibility of satellite damage during rocket launch;
- incorrect satellite assembling
  - possibility of satellite damage during rocket launch;
  - possibility of cable disconnections between subsystems;

  - possibility of MLI insulation damage – future thermal problems;

6.4.7 Communication system (COMM) failure

- transmission error, no signal from Earth
  - Sail deployment command is send from Earth;
  - In case of lack of communication in both directions, sail will deploy automatically after certain time;

6.4.8 Payload failure

- failure of elements responsible for camera operation
  - no photos from camera;
- failure of elements responsible for sun sensor
  - lack of readings from SunS;

6.5 Further Work

Next steps of risk analysis should be:

- Detailed assessment of possible unwanted events in each team;
- Identification of causes of identified unwanted events;
- Identification of unwanted events detection method;
- Classification of identified unwanted events according to threat level of mission success;
- Classification of identified unwanted events according to probability of occurrence;
- Identification of criticality of identified unwanted events;
- Accurate analysis of the most critical unwanted events (ex. Use of tree event method and tree errors method);
- Identification of risk lowering methods for critical unwanted events;
- Identification and analysis of unwanted events occurring during subsystems interaction and cooperation.

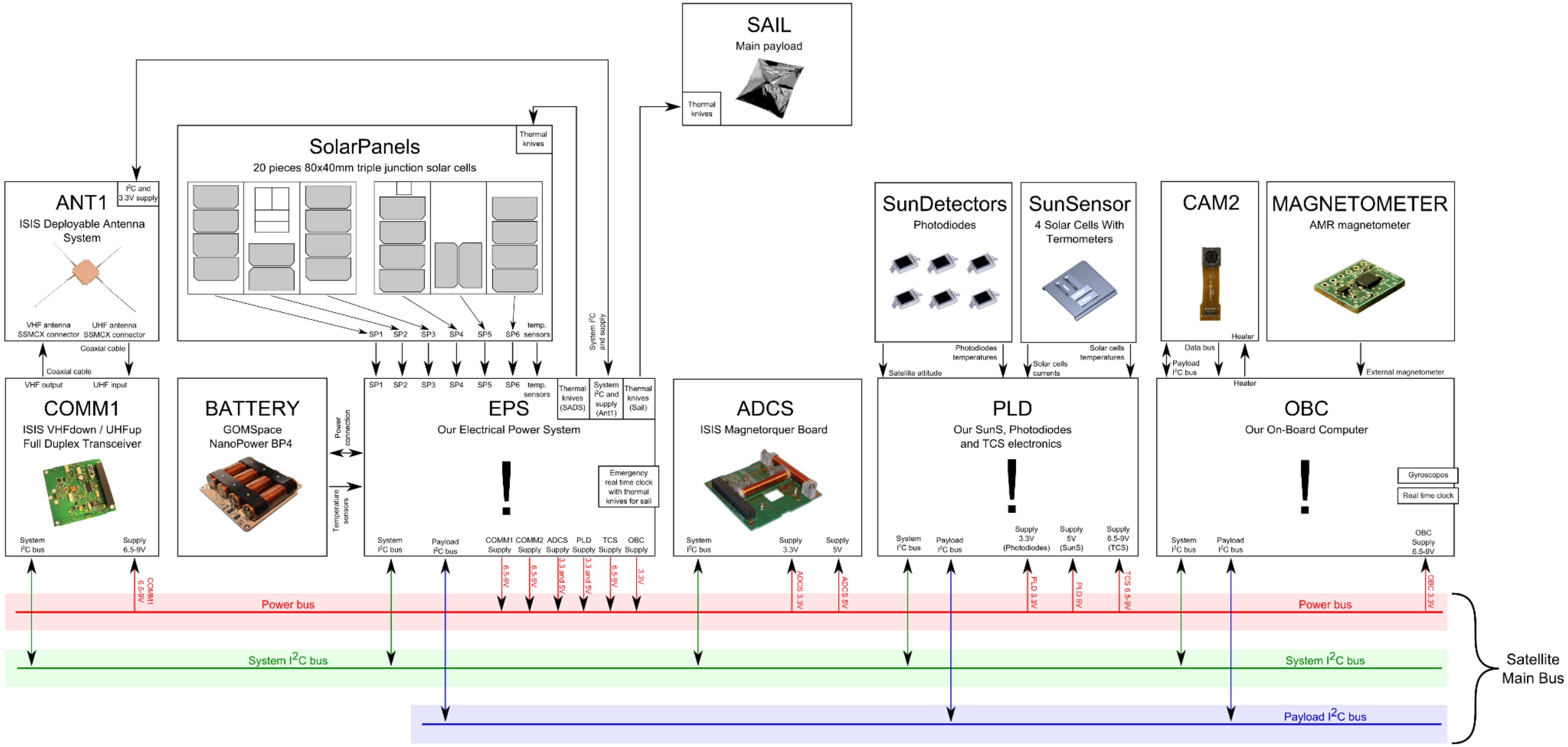
7 APPENDIX

Appendix 1 Teams, their leaders, supervisors and advisors. Number of people involved in brackets.

Team	Full team name	Team leader	Number of members	Team Supervisors (Warsaw University of Technology)	Team Advisors	Other
ADCS	*Attitude Determination and Control System*	Paweł Jaworski	6	Division of Mechanics, MEiL/PAE [1] Division of Automation and Aeronautical Systems, MEiL/PAE [1]	Electronics Constructions Laboratory [1]	ISIS [1]
CAM	*Cameras*	Mateusz Sobiecki	4			
COMM	*Communication*	Tomasz Rybarski	11	Institute of Radioelectronics, EiTI/FEIT [1]	Laboratory of Satellite Applications of FPGA [1]	
DT	*Deployment Team*	Ewelina Ryszawa	15	Institute of Micromechanics and Photonics, Mechatronics [1] Department of Mechanics, SiMR [1] Institute of Machine Design Fundamentals, SiMR [1] Faculty of Materials Engineering [1]		
EPS	*Electrical Power System*	Piotr Kuligowski	5	Institute of Electronic Systems, EiTI/FEIT [1] Institute of Microelectronics and	Nicolaus Copernicus Astronomical Center [2]	

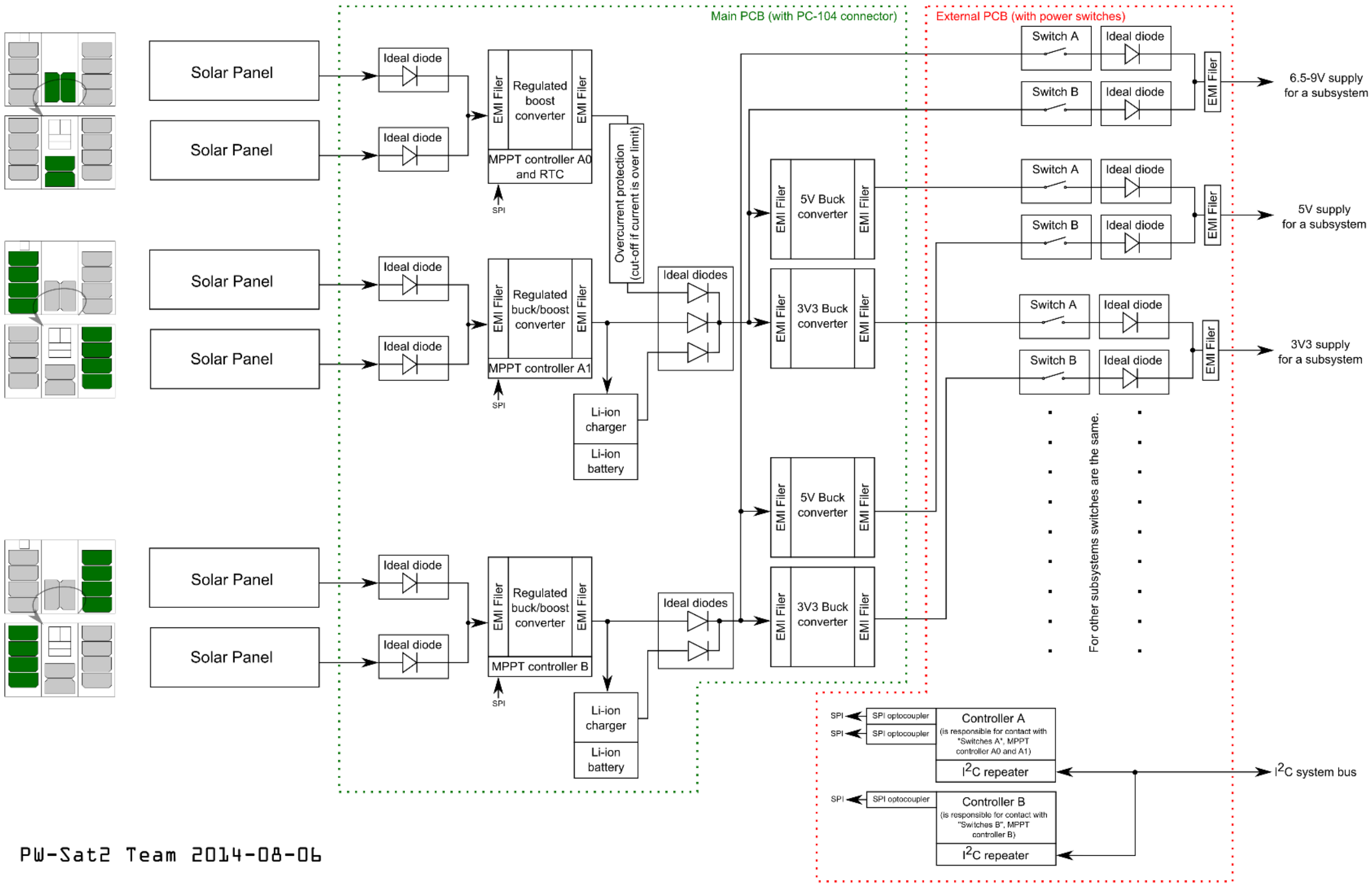
				Optoelectronics, EiTI/FEIT [1]		
GS	*Ground Station*	Tomasz Rybarski	11	Institute of Radioelectronics, EiTI/FEIT [1]	Nicolaus Copernicus Astronomical Center [1]	
MA	*Mission Analysis*	Artur Łukasik	7		Nicolaus Copernicus Astronomical Center [2]	
OBC	*On-Board Computer*	Piotr Kuligowski	10	Institute of Electronic Systems, EiTI/FEIT [1]		
PR	*Public Relations*	Dominik Roszkowski	7			Krzysztof Karaś
SunS	*Sun Sensor*	Inna Uwarowa	10	Institute of Microelectronics and Optoelectronics, EiTI/FEIT [1]		
TCS	*Thermal Control System*	Alan Budzyński	1			

Appendix 2 Flowchart of the PW-Sat2 systems

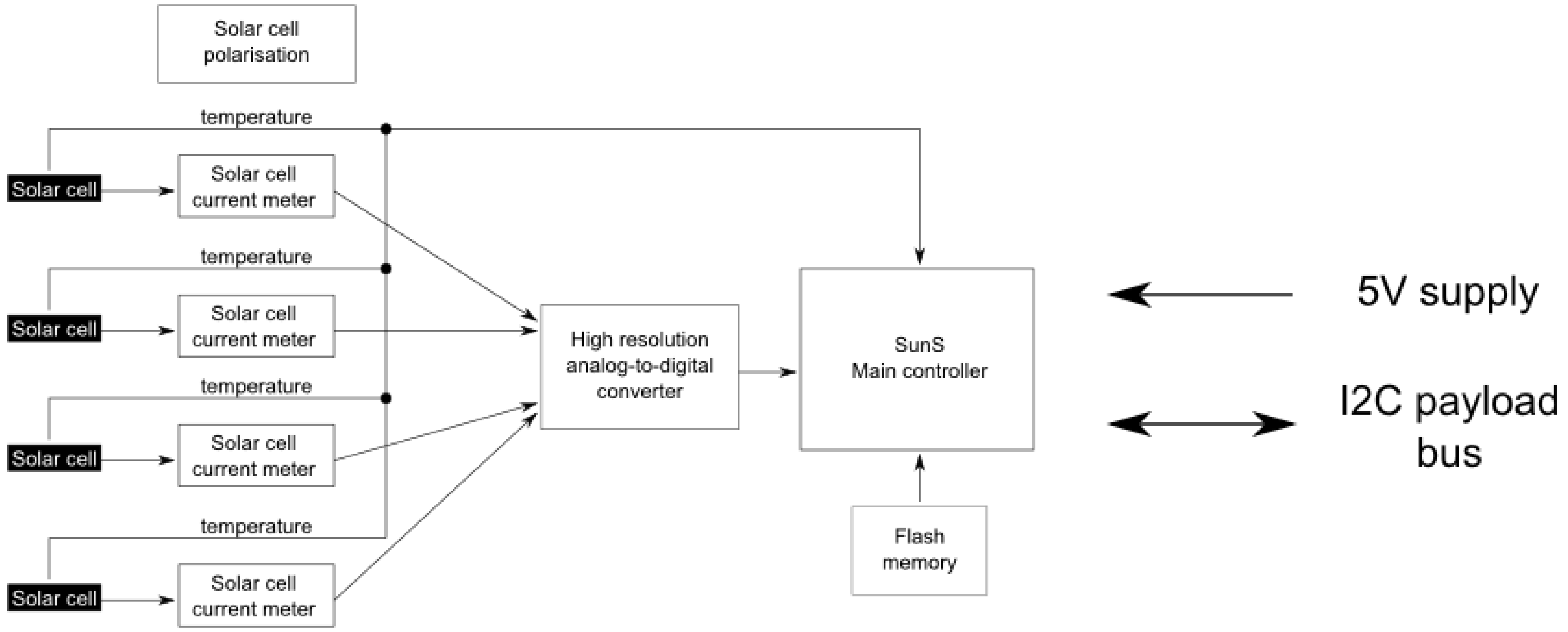


PW-Sat2 Team 2014-08-05

Appendix 3 Flowchart of Electrical Power System



Appendix 4 Flowchart of the SunS system



Appendix 5 Case 1 of financial budget of PW-Sat2 project

Team		Components			Price			Total	
BUS	OBC	Prototypes			1 666,67 €	2 857,14 €		39 595,57 €	51 202,62 €
		Flight version			1 190,48 €				
	EPS	Prototypes			2 380,95 €	13 771,43 €			
		Flight version			1 190,48 €				
		Solar panels			8 700,00 €				
		Batteries (4 pax)			1 500,00 €				
	COMM	~~S-Band~~			~~0,00 €~~	11 750,00 €			
		~~S-Band antenna~~			~~0,00 €~~				
		UHF/VHF			7 250,00 €				
		UHF/VHF antenna			4 500,00 €				
	ADCS	Full service			8 000,00 €	8 000,00 €			
	Struct	Test version (3D printer)			167,00 €	3 117,00 €			
		Flight version			2 950,00 €				
	TCS	MLI			100,00 €	100,00 €			
Payload	DT	Sail	Case + deployment system	Prototypes	166,67 €	5 880,95 €	7 380,95 €	11 607,05 €	
				Flight version	952,38 €				
			Material		1 190,48 €				
			Springs		3 571,43 €				
		SADS	Mechanism + springs	Tests	500,00 €	1 500,00 €			
				Flight version	1 000,00 €				
	SunS	Słonecznik	Structure		369,00 €	488,00 €	3 392,76 €		
			Other		119,00 €				
		Test stand	Solar cells (tests)		285,71 €	1 690,48 €			
			Mechanical		880,95 €				
			Electonic		523,81 €				
		SunS-stand	Interface (tests)		71,43 €	190,48 €			
			Interface (flight version)		119,05 €				
		Sensor	Prototype		309,52 €	1 023,81 €			
			Flight version		714,29 €				
	CAM	~~CAM1~~			~~0,00 €~~	833,33 €			
		CAM2			833,33 €				
Other	PR				500,00 €	500,00 €		238 595,24 €	
	Launch				238 095,24 €	238 095,24 €			
Total								289 797,86 €	

Appendix 6 Case 2 of financial budget of PW-Sat2 project

Team		Components			Price			Total	
BUS	OBC	Prototypes			1 666,67 €	2 857,14 €		39 595,57 €	53 702,62 €
		Flight version			1 190,48 €				
	EPS	Prototypes			2 380,95 €	13 771,43 €			
		Flight version			1 190,48 €				
		Solar panels			8 700,00 €				
		Batteries (4 pax)			1 500,00 €				
	COMM	~~S-Band~~			~~0,00 €~~	11 750,00 €			
		~~S-Band antenna~~			~~0,00 €~~				
		UHF/VHF			7 250,00 €				
		UHF/VHF antenna			4 500,00 €				
	ADCS	Full service			8 000,00 €	8 000,00 €			
	Struct	Test version (3D printer)			167,00 €	3 117,00 €			
		Flight version			2 950,00 €				
	TCS	MLI			100,00 €	100,00 €			
Payload	DT	Sail	Case + deployment system	Prototypes	166,67 €	5 880,95 €	7 380,95 €	14 107,05 €	
				Flight version	952,38 €				
			Material		1 190,48 €				
			Springs		3 571,43 €				
		SADS	Mechanism + springs	Tests	500,00 €	1 500,00 €			
				Flight version	1 000,00 €				
	SunS	Słonecznik	Structure		369,00 €	488,00 €	5 892,76 €		
			Other		119,00 €				
		Test stand	Solar cells (tests)		285,71 €	1 690,48 €			
			Mechanical		880,95 €				
			Electonic		523,81 €				
		SunS-stand	Interface (tests)		71,43 €	190,48 €			
			Interface (flight version)		119,05 €				
		Sensor	Prototype		309,52 €	3 523,81 €			
			Reference sun sensor		2 500,00 €				
			Flight version		714,29 €				
	CAM	~~CAM1~~			~~0,00 €~~	833,33 €			
		CAM2			833,33 €				
Other	PR				500,00 €	500,00 €		238 595,24 €	
	Launch				238 095,24 €	238 095,24 €			
Total								292 297,86 €	