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PW-SAT2

PRELIMINARY REQUIREMENTS REVIEW

Electrical Power System

Phase A of PW-Sat2 project
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Abstract

The following paper is a part of Phase A Summary of student satellite project PW-Sat2. The document presents the proccess of designing and building the first version of the Electric Power System (EPS).

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Attention Phase A documentation may be outdated in many points.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

This document is also available in Polish.

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1 INTRODUCTION

Electrical Power System (EPS) converts energy from the solar cells, recharges the batteries, converts the voltage and supplies power to other subsystems. At the beginning of the project it was determined, that PW-Sat2 satellite will be made in Cubesat 2U standard and solar cells will be placed on the deployable surfaces and walls of the satellite.

The task of the EPS Team is to design and build a working subsystem, which will be placed on board of the PW-Sat2 satellite.

This document presents an analysis of the power system architecture selection based on mission requirements and the analysis EPS of other CubeSats. The batteries was selected and the power budget was determined. Also the converter prototype tracking the maximum power point from solar cells was described.

The power supply system has high demands of reliability. Its failure could lead to the end of the mission without success. To avoid this number of safeguards have been applied. First of all is the redundancy of basic EPS blocks: two independent battery packs and two independent chargers. Even when all the microcontrollers included in the structure are damaged, the power system is able to power basic subsystems.

At the end of phase A of the project the main camera CAM1 and S-Band transceiver for sending large data volumes were rejected.

2 EPS IN CUBESAT SATELLITE MISSIONS

Design of the power supply (EPS – Electrical Power System) depends on the quantity of other components of the satellite and their power consumption, the solar cells area and available space for the battery pack. The analysis of several satellite missions in Cubesatstandard with description of design solutions is presented below.

2.1 SWISSCUBE POWER SYSTEM

SwissCube (http://swisscube-live.ch) is designed in Cubesat 1U standard, which is in the form of a cube of side 10cm.On the five of the satellite walls there are placed triple junction solar cells with high efficiency (about 30%).

The maximum power possible to obtain on one wall is 1,74W:

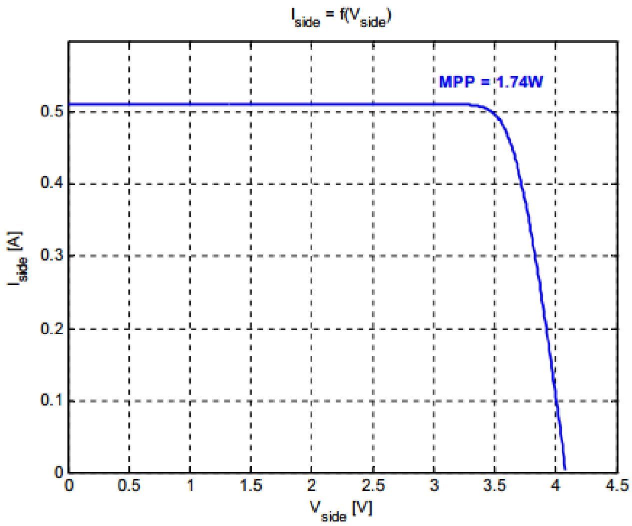
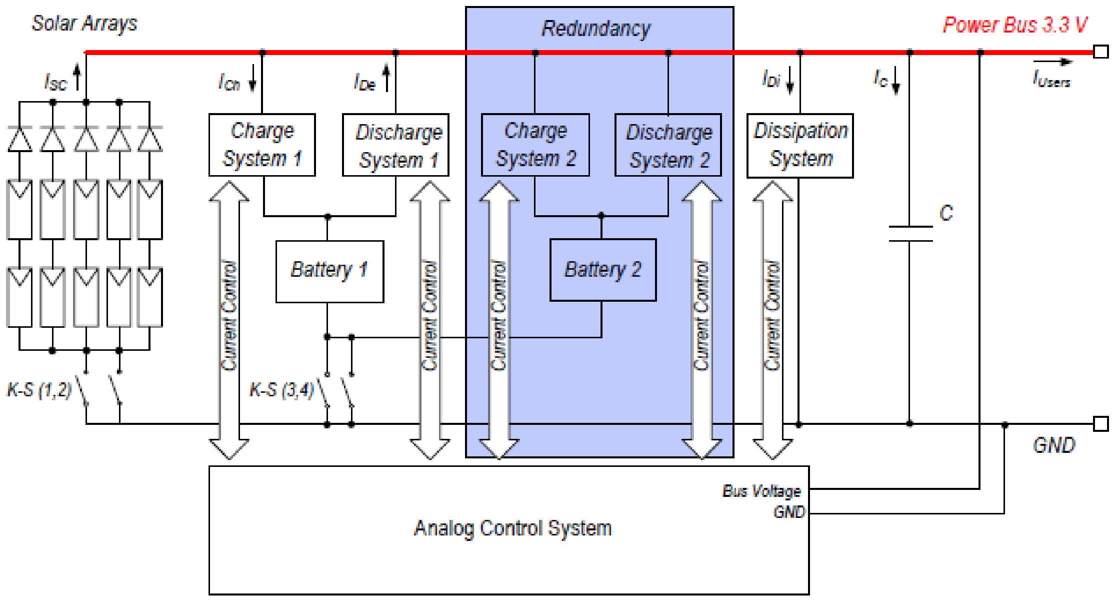


Figure 4-8 : I-V characteristic of one side of the satellite (G=1350W/m², T=75°C)

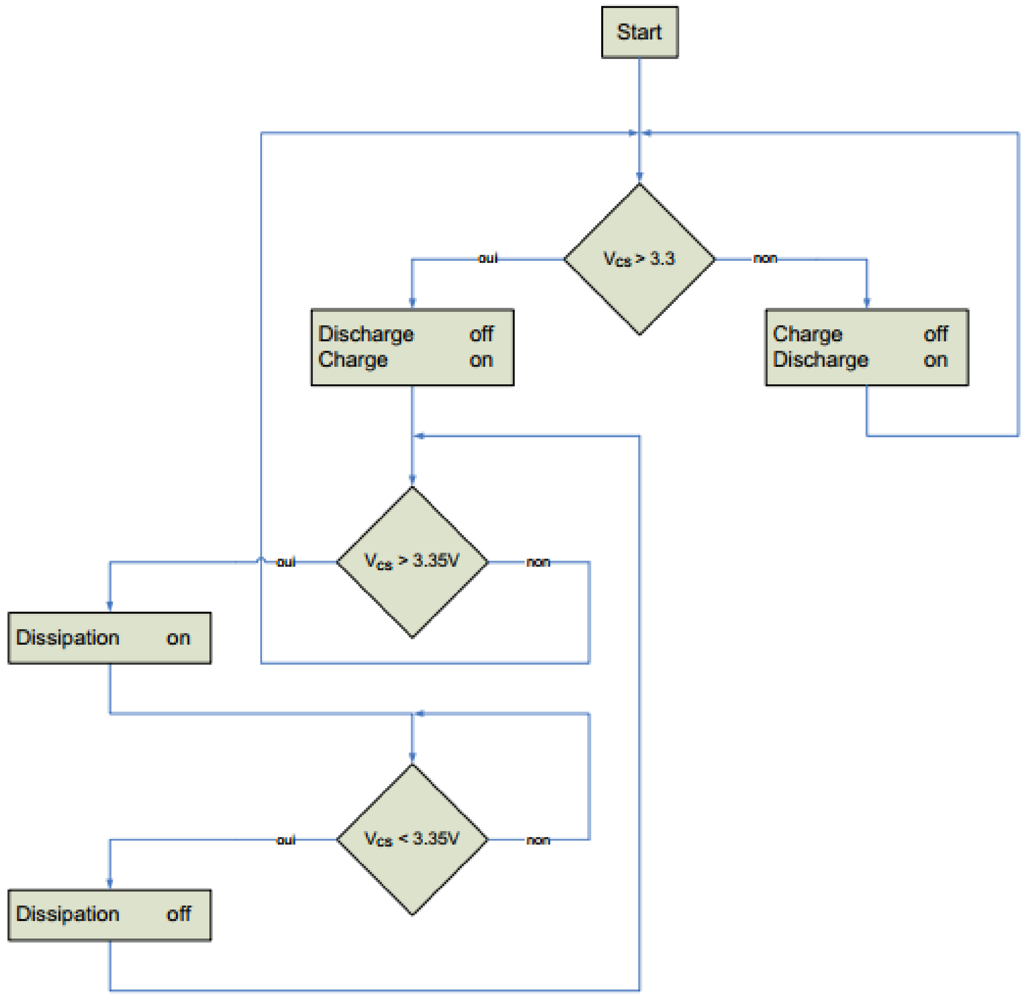
A one moment three walls can be illuminated, but only one can be faced directly at the Sun. If the light is at the right angle to the wall, maximum power on this wall is obtained. The other two walls has much less energy, because the sun shines at an angle other than 90 degrees.

The solar cells located on one wall are serially connected with a protective diode.Five solar cells systems formed in this way are connected to a main supply rail 3,3V.

Block diagram of SwissCube-1



In the diagram above on the left are solar cells mentioned earlier. They are connected to the main power rail 3,3V. Next are two redundant systems of converters chargers (Charge System) and batteries dischargers(Discharge System) and Dissipation System to dissipate excess power. The analog system controls the chargers, dischargers and dissipation systems in order to maintain the voltage 3,3V on the main power supply rail. Below is a block diagram from SwissCube documentation, visualising the idea:



In the power supply system there were not applied independent converters tracking solar cells maximum power point (MPPT converters). The voltage 3,3V on the power rail determines the solar cells operating point near to maximum possible power, adding the voltage drop on the solar cells serial diode. This eliminates the additional converters, but the minus is that power is only from the most illuminated solar cell.

The components used

- Rechargeable lithium-polimer battery VARTA PoLiFlex PLF503759, with a maximum voltage of 4,2V i a capacity of 1210mAh. Battery depth of discharge (DOD) was limited to 30% in order to increase the lifetime and reliability:

Here is the typical charge profile of a PoLiFlex battery and the voltage range for a DOD of 30%:

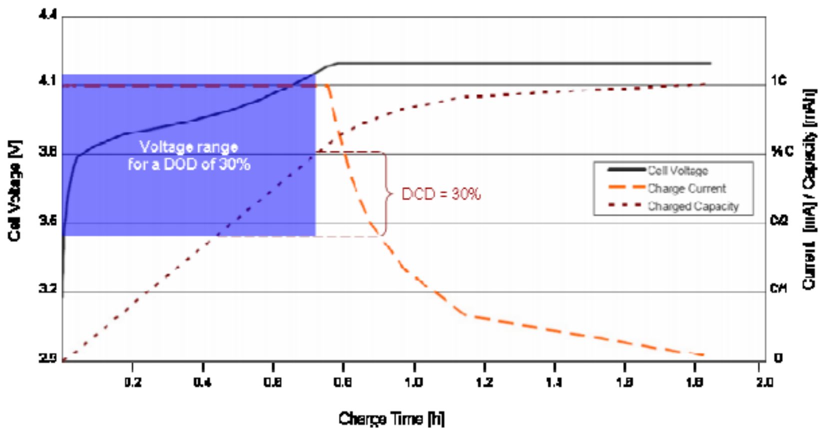


Figure 5-5 : Typical charge profile (1C, 20°C) with the defined voltage range for the application

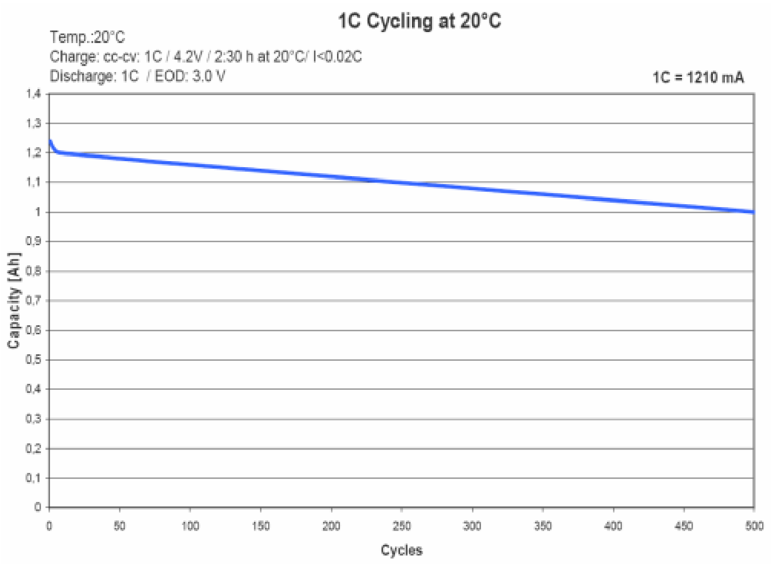


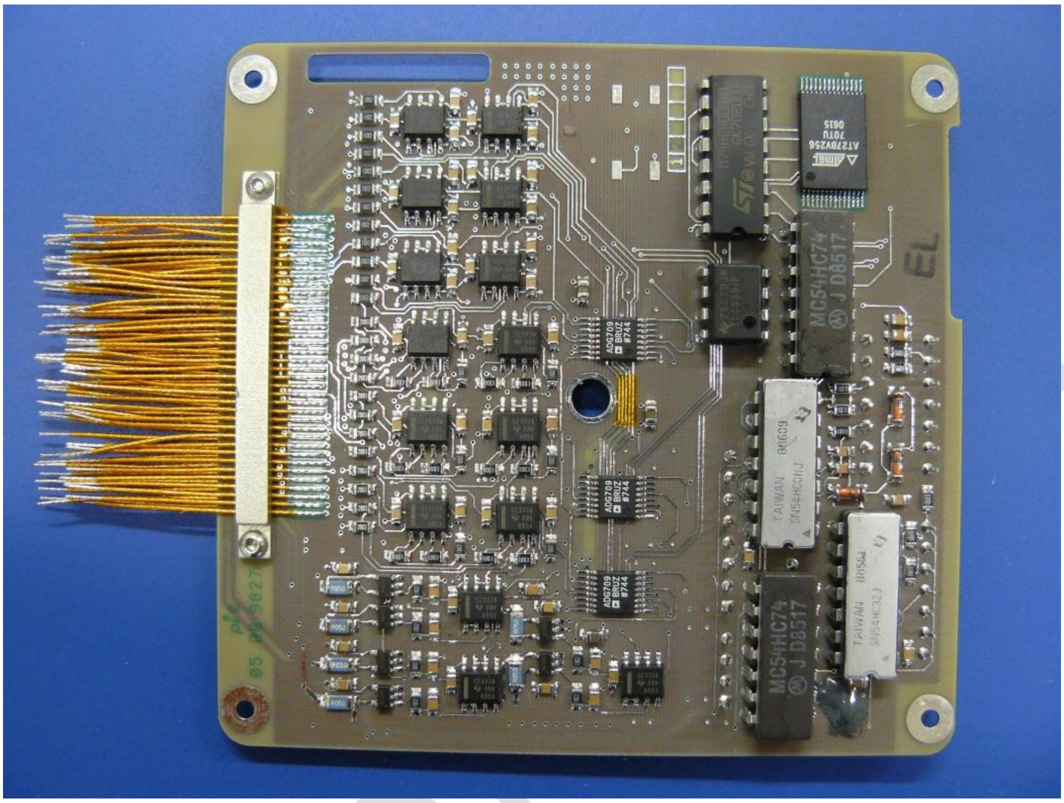
Figure 5-9 : Life expectancy (1C, @20°C)

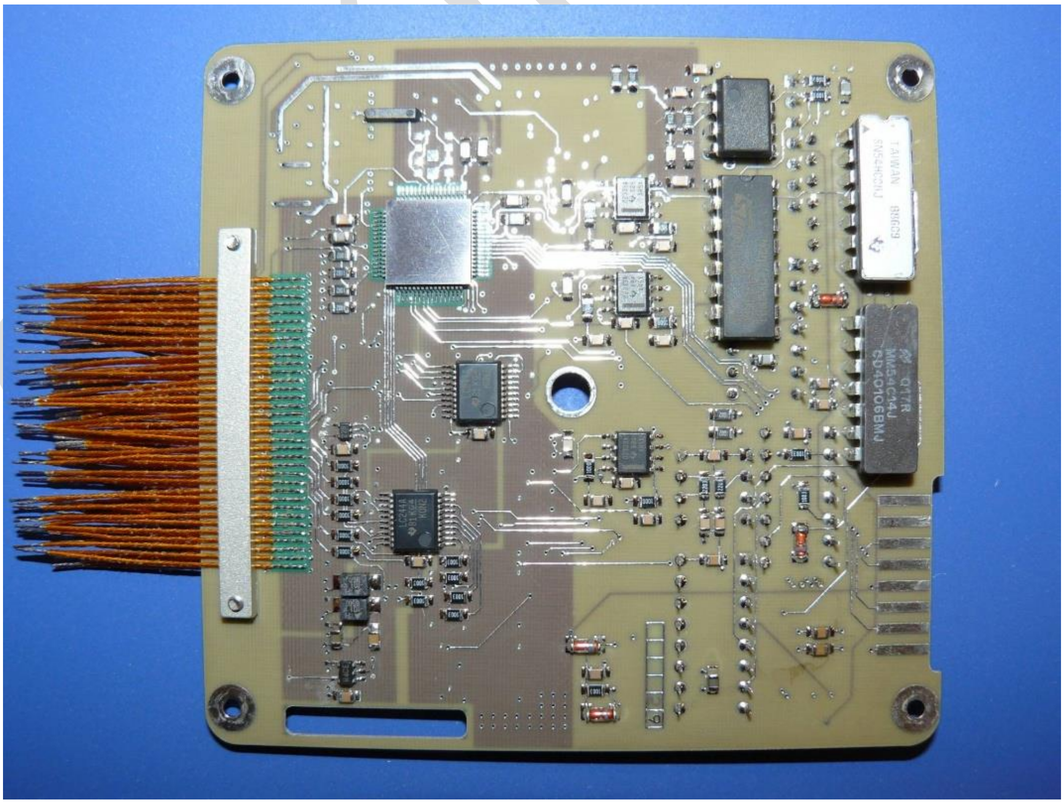
On Low Earth Orbit satellite takes about 15 cycles around the Earth for a day, nearly 5500 per year. In each cycle for some time the solar cells are illuminated and for some time shaded. Charging cycles cause a drop in battery capacity.

- Battery charger – converter LTC3421 in a boost configuration (increasing voltage) with an external analog control system.

- Discharger, or a system supplying the power bus from a battery – converter on LTC3414 in buck configuration (decreasing voltage) with an external analog control system.

- Excess power dissipating system – a current source build of a bipolar transistor, resistor and operational amplifier.





Conclusions

The power supply system designed by SwissCube team was very simple and reliable at the same time. The satellite was launched in late 2009 and the last communication session was held in August 2013. This is very good result and a proof of the reliability of the solutions.

2.2 ESTCUBE-1 POWER SUBYSTEM

ESTCube-1 satellite (http://www.estcube.eu) was made in Cubesat 1U standard. It has 12 solar cells, two on each wall. The architecture of power supply system is more efficient than in SwissCube.

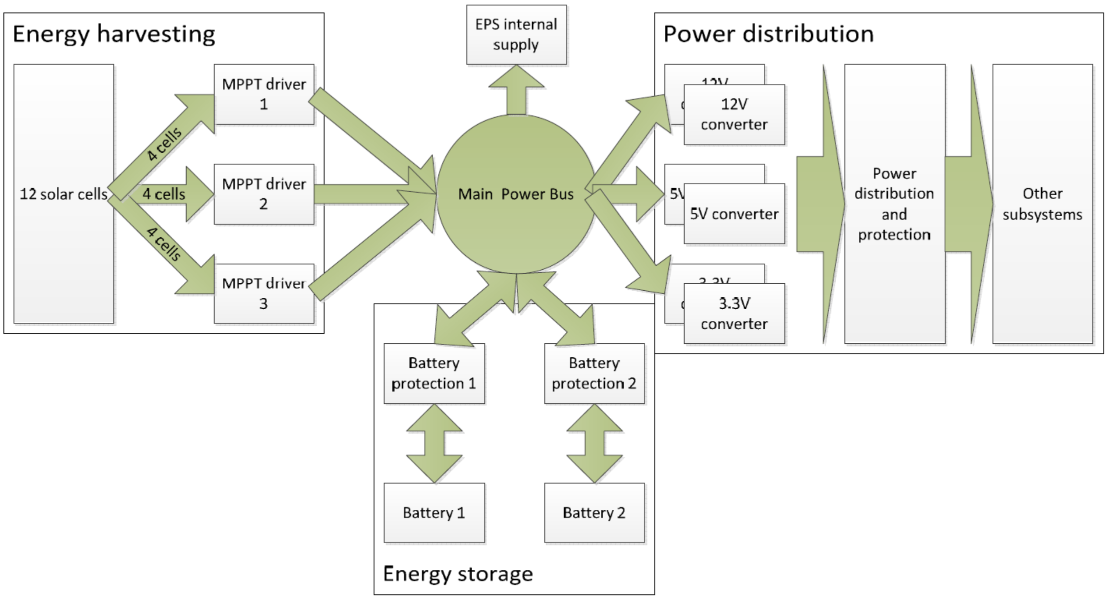
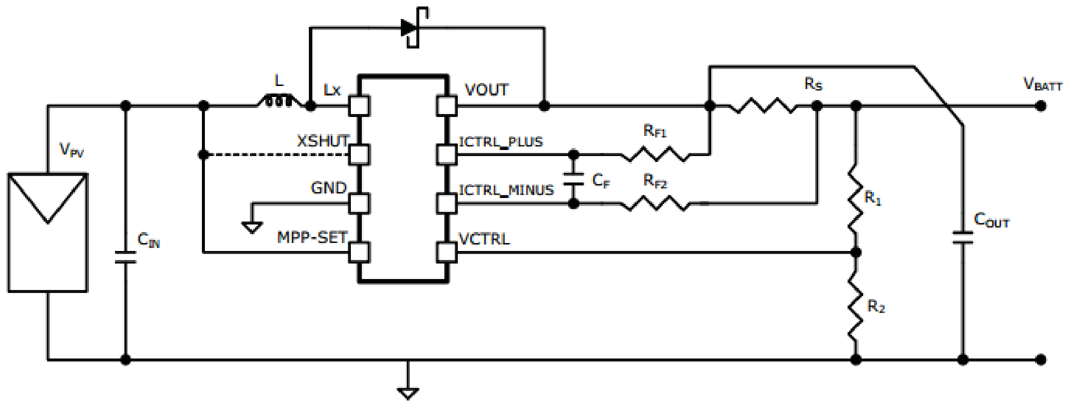


Fig. 1: General schematic of the Electrical Power System of ESTCube-1 showing the major blocks and their constituents [6].

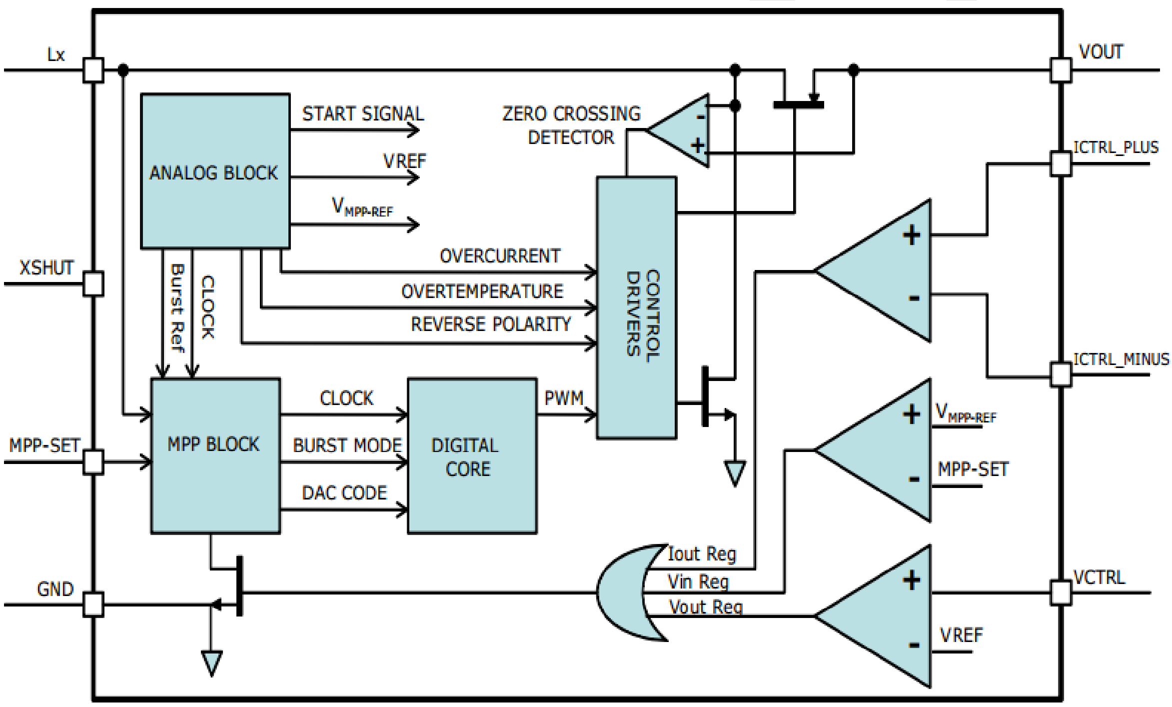
Solar cells from walls on opposite sides are connected to one converter tracking the maximum power point (MPPT) by summation system build with ideal LT4352 diodes. This allows to limit the number of MPPT converters to three.

MPPT converter

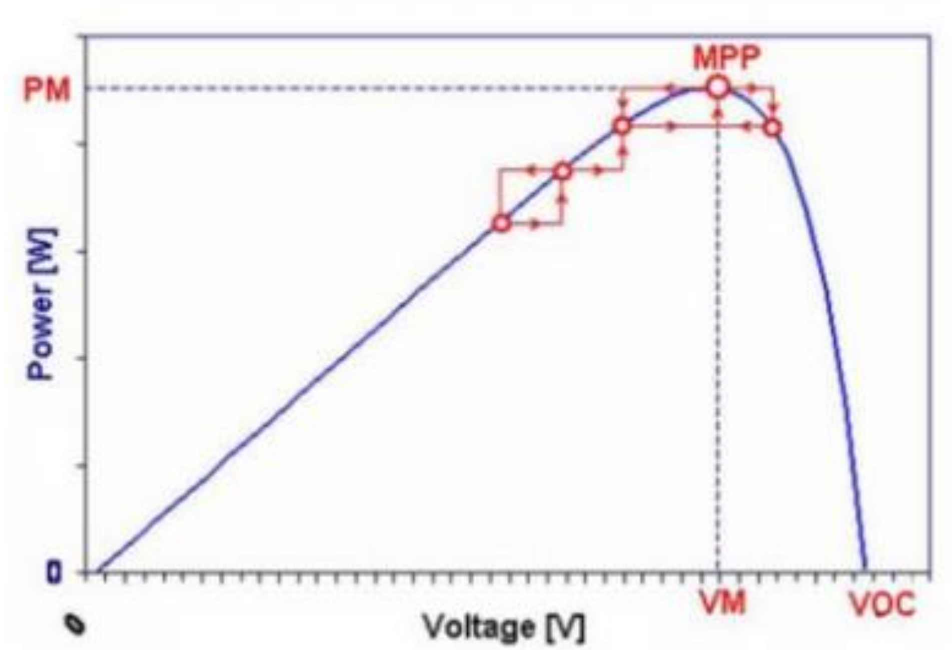
The previously mentioned MPPT systems were realized on SPV1040 from STMicroelectronics. It is a converter merged with the maximum power point tracking controller.



Converter operates in the voltage increasing configuration (BOOST) as a battery charger. Efficiency above 95% was achieved by placing the ideal diode inside the structure.

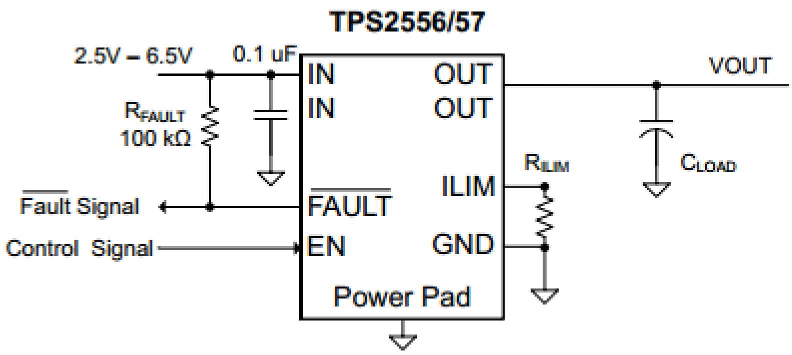


Algorithm of maximum power point tracking:



Batteries and chargers

Energy is being stored in two cylindrical batteries Lithium-Ion P-CGR 18650C Philips. For switching and batteries over-current protection were used TPS2557 switches systems:



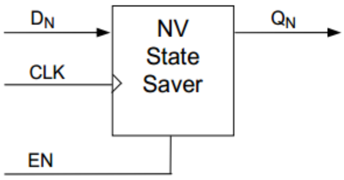
This system is a MOSFET power switch with adjustable over-current protection. Supply voltage range is 2,5-6,5V, conduction currents range is between 500mA and 5A. Output $\overline{FAULT}$ indicates irregularities. The system is dedicated for USB solutions.

Power distribution

Voltages of 3,3V and 5V are produced by the combined pairs of BUCK-BOOST converters type LTC3440. Converter LM2700 generates 12V, operates in BOOST configuration and is controlled within +/-10% by the microcontroller's digital to analog converter connected to the feedback.

Subsystems power supply is activated by TPS2557 keys with adjustable current limit. FM1105 systems store keys configuration. FM1105 remember a key state before the power outage and restores its state when power returns. The configuration is stored in the internal FRAM memory. This allows the power system to restore its state before the power failure.

FM1105 chip:



INPUTS			OUTPUT
EN	CLK	Dn	Qn
H	↑	L	L
H	↑	H	H
H	H or L	X	Q_0
L	X	X	Hi-Z

L Low voltage level
H High voltage level
X Don't Care
↑ CLK rising edge
Q_0 Previous output state before CLK ↑

Supply system supervision

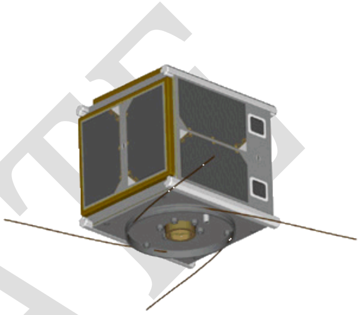
The supply system is controlled by the ATMega1280 microcontroller. The internal power was expanded with an external parallel memory FRAM FM18W08. The configuration is stored in memory FM2526 SPI from RAMTRON and the power keys state is stored in FM1105.

The microcontroller's power supply is equiped with a super capacitor, which delays the computer turning off and allows it to react to the situation.

Conclusions

The designers of the power supply system are trying to get higher resistance to radiation by application FRAM memory in many places. Reliability is achieved by redundancy of supply system blocks. The mission lasts from May 2013 until now (March 2014) and the satellite is operational.

2.3 AAU-CubeSat supply system

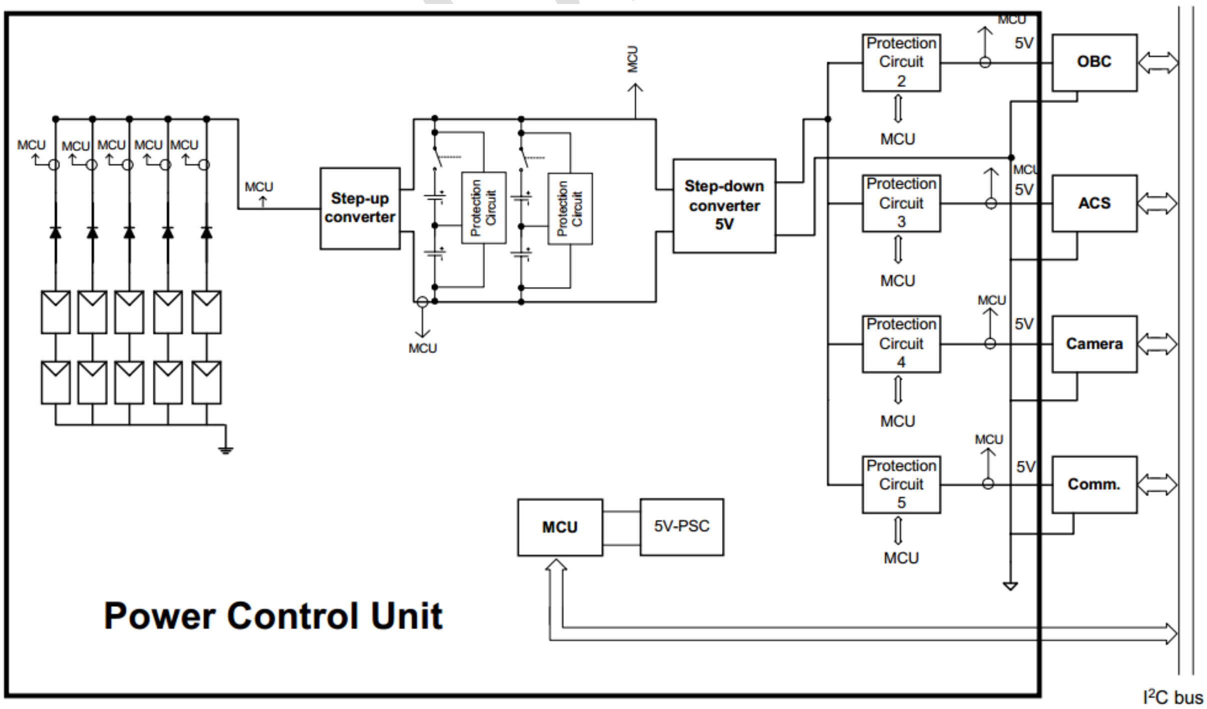


AAU-CubeSat (http://www.space.aau.dk/cubesat) was launched in June 2003. It was made in Cubesat 1U standard. It's main task was to take a photo of the Earth's surface.

After placing in orbit a stable radio connection was not established, probably because of communication module.

On each of the five walls were placed two solar cells. All of them, as in the case of SwissCube were connected to one bus by protection diodes.

Next is the boost converter and two redundant battery packs. Each has a safety system. Next buck converter produces a voltage of 5V, which is distributed to the other subsystems. Security systems are on all of the power lines, supplying the other sub-systems.



The supply system communicates with the computer via the I²C bus.

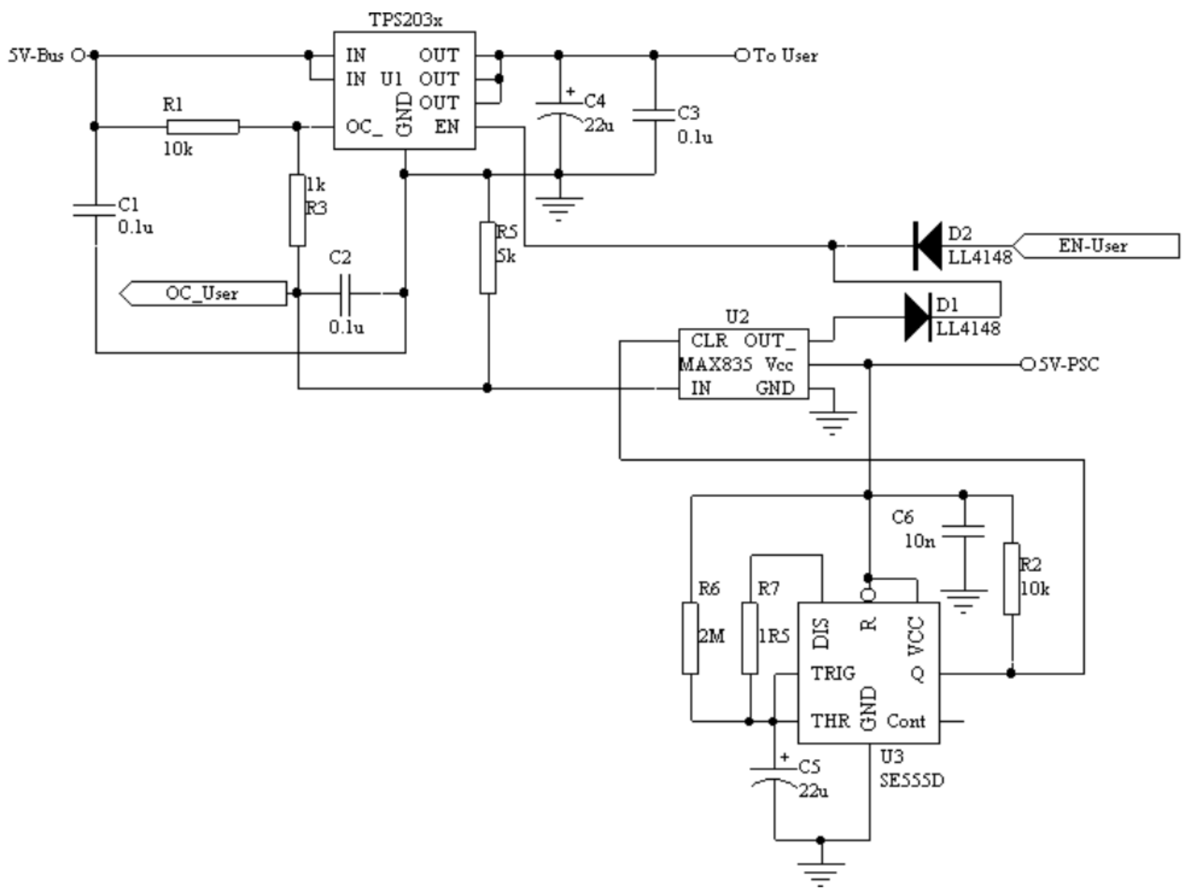
MPPT converter and batteries

As MPPT converter MAX1771 was used. ADP3810 is responsible for charging the batteries. UCC3911 system protects the batteries from overcharging, reverse polarity, over-discharging etc.

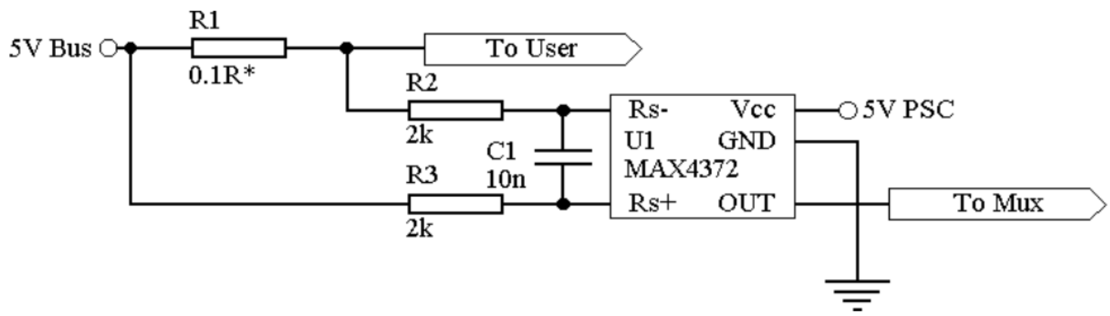
5V converter and power distribution

The 5V converter supplies power subsystems of the satellite. As converter's controller was used MAX1744. As overload protection and power-switches was used TPS203x. As power monitor was used MAX835. It is fault detector of the power-switch. SE555D is responsible for power switch-on after fault.

Block diagram of the power distribution system:



LM19 is responsible for temperature measurements, MAX4372 is responsible for current measurements:



Microchip PIC16C774 is main chip. It has 4kB program memory, 4kB EEPROM memory and 256B RAM memory.

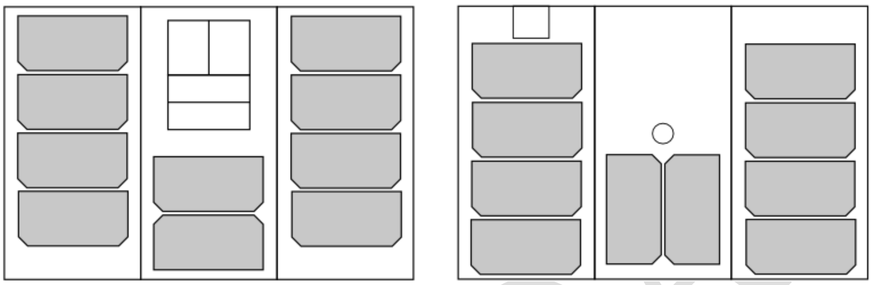
Conclusions

It is not fully redundant supply system. It is very seriously design flaw.

3 Electrical Power System architecture

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 distribute 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.

Possibility of connection 6 solar panels distributed as shown below:



On every surface solar cells is connected in series. There will be 3-junction cells with effectiveness about 30%. Maximal theoretical power from each of the cells is 1W. Maximal power of 1 panel containing 4 cells is 4W.

Tracking of maximal point of power MPPT of each surface of solar panels. System should have it's maximal possible power, which will be achieved by using boost converters controlled by microcontroller.

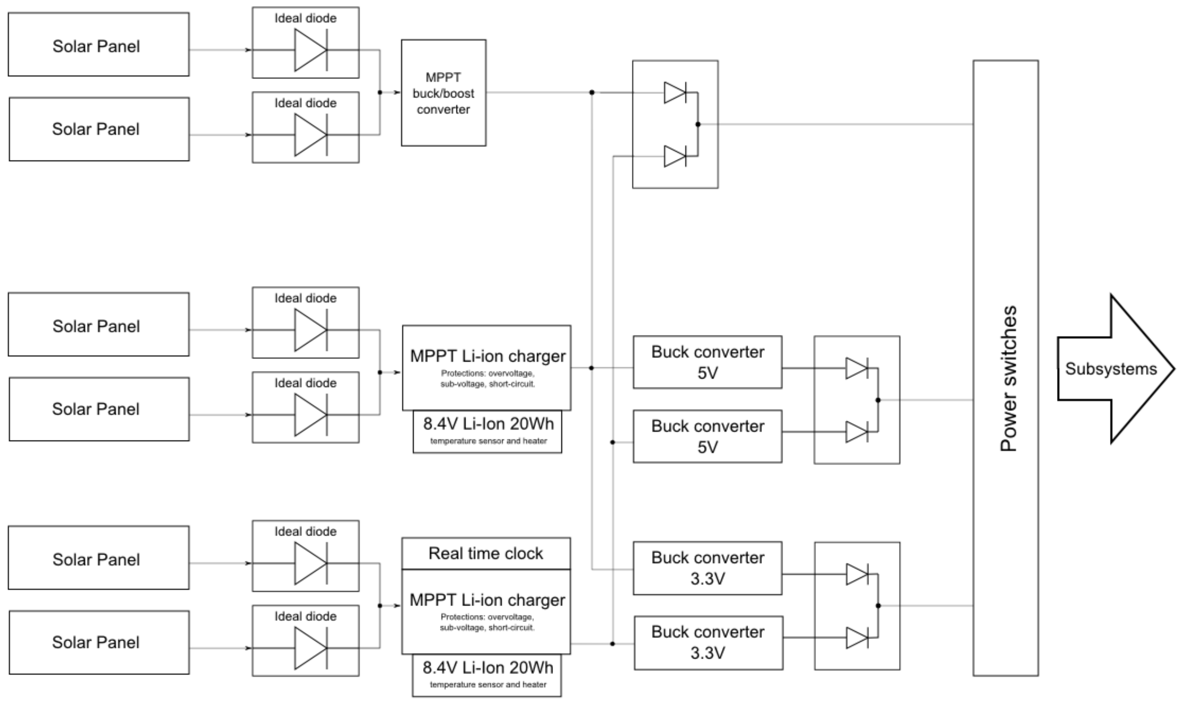
OBC responsible for power budget monitoring. OBC is the supervisor for electrical power system. EPS is responsible for switch-on or switch-off electrical power and it is responsible for battery charging. Power-switches are controlled based on commands from the on-board computer.

EPS controls turning on and off the power and reacts to critical situations (battery's voltage is critically low).

Module will function in vacuum environment with large temperature gradient (-40°C to +60°C) and increased ionizing radiation.

Redundancy of basic, critical sections of power system is very important. 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.

3.1 Block diagram



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

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. To increase reliability of E 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).

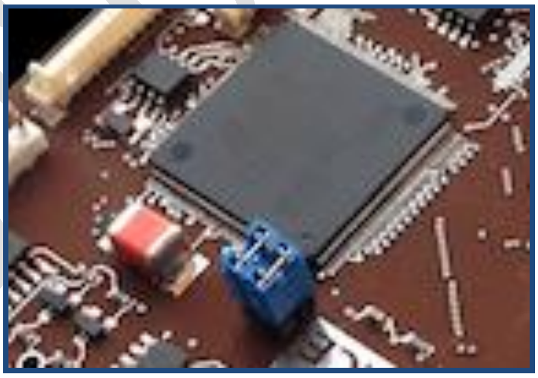
Buck converters are responsible for creating voltages 3.3V, 5V from battery voltage. Buck converters are redundant.

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, co they have to have their own hardware protection.

EPS microcontroller – it is only EPS's monitor. It is responsible for measurement of currents, voltages and temperatures.

EPS's real time clock – it is time counter. It is responsible for mission-protection. As RTC we will use internal RTC of EPS's microcontroller. 30 days after separation it will open sail. RTC and protection-circuit have independent power system. As RTC backup we will use super-capacitors):

Similar solution was used by GOMSpace. It is backup RTC's of on board computer:

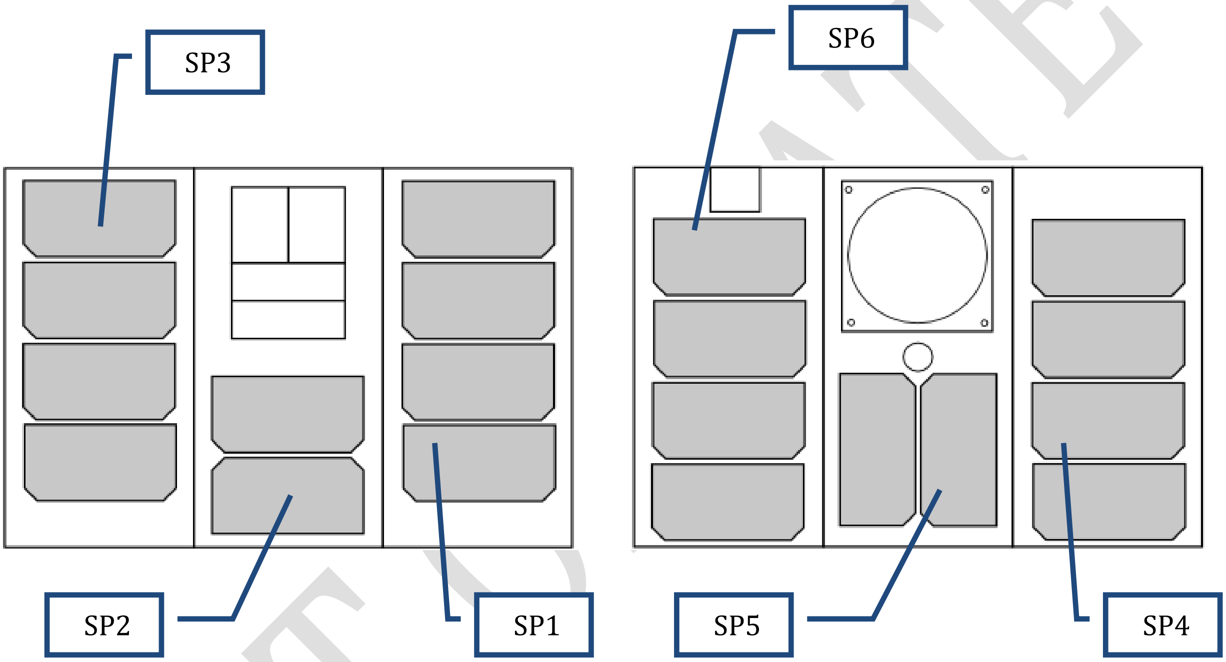


4 POWER BUDGET

Below is an analysis of power budget. Calculated available energy per single orbit. Next calculated circuits's losses and power consumed by each module. On this basis, the proposed power budget planning.

4.1 SOLAR PANELS

Location of solar panels is shown on pictures below:



On each of selected surfaces solar panels can be placed. It is possible, according to thermal analysis by TCS team.

Solar panels spread out perpendicularly.

If sun sensor of PW-Sat2 is directed to the sun, solar panels are lightened up. Panels on surfaces no. 4, 5, 6 seem to be unnecessary. However, tracking sun in 3 axis is not possible, because of magnetic system of control (ADCS). Even if 3-axis system would be applied, it can not control all axis simultaneously. Because of that, a satellite will rotate around one of them and panels on surfaces no. 1,2 and 3 will be lighten periodically, the same as on the surfaces 4, 5 and 6. That's why solar panels should be placed on surfaces 1-6.

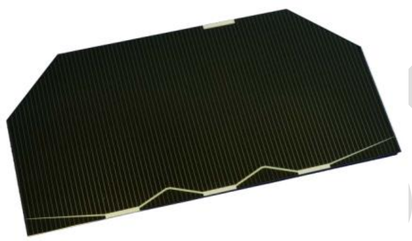
Solar panels spread out at another angle than 90 degrees.

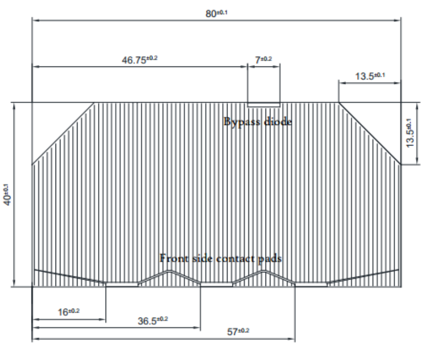
Further analysis will show the proper angle, in order to remove panels 4 and 6. It will reduce cost, mass and structure complication.

Availability of solar panels.

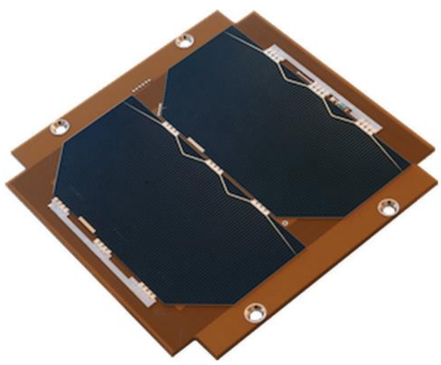
Conversations with single panels / whole panel structures providers.Offer single panels when order of 30 pieces.:

Company	Characterictics	Price per unit
AzurSpace (Germany)	Efficiency 30%, dimensions 80x40mm	270€
CESI (Italy)	Efficiency 30%, dimensions 80x30mm	280€





There is a possibility of making prepared modules of solar panels. On a picture below an example of prepared module of wall 1U from GOMSpace comapany:



Price for a single module is about 2000€.

Solar panels are very fragile and it's very easy to damage them. It is a good solution to buy complex module.

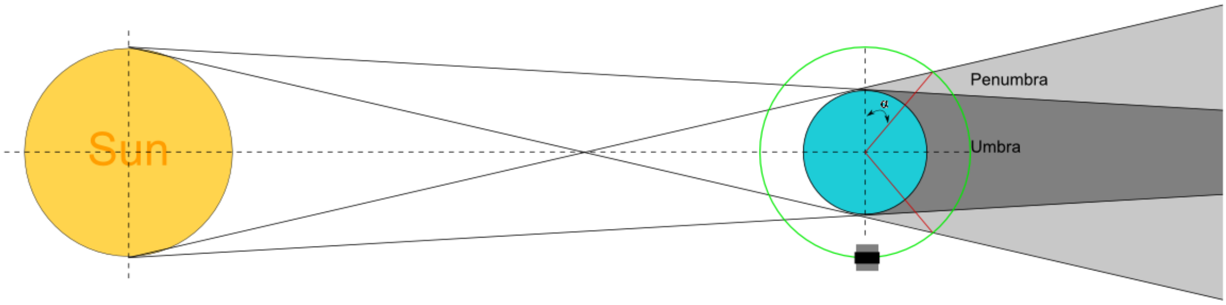
4.2 Energy from solar panels per single orbit

Generated energy per one orbit depends on many factors. Besides orbit, there's temperature and orientation control. When temperature increases, efficiency of solar panels decreases. If sun tracking stem is not tracking the sun properly, the satellite could rotate in random way. The main purpose of this section is a calculation of generated energy per one orbit in order to simplify further calculations.

The unit of this energy will be watt*second(Ws), or joule. It should define energy obtained while coming through the whole orbit. The result can be easily converted to watt-hours, by division the result by 3600s.

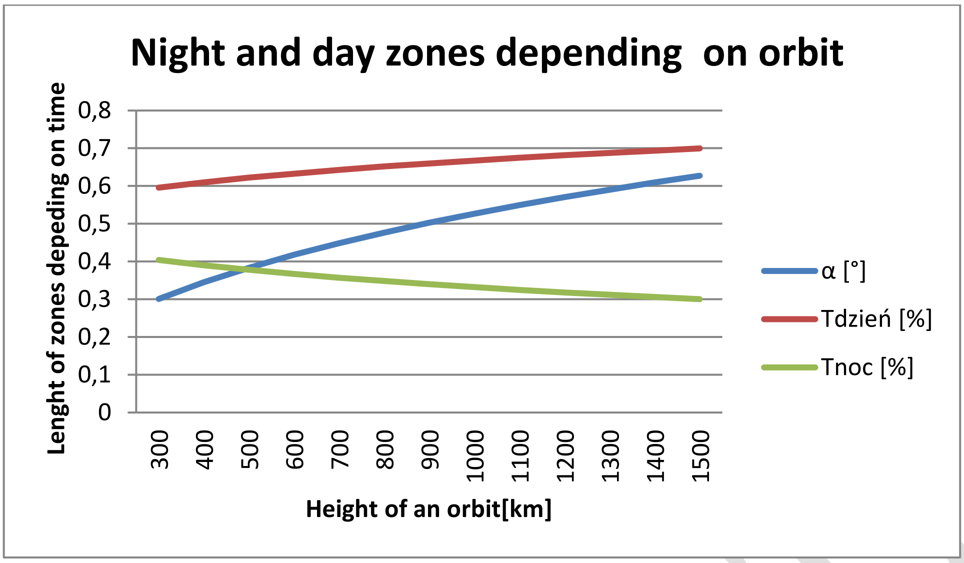
4.2.1 Day and night zones

While rotating around earth, satellite will periodically come in and out to a day zone and shadow zone. A shadow is a cone of total blackout(umbra), penumbra is a cone of semi-darkness. Penumbra is negligibly small, so it was not concerned in calculations.



$\alpha = \arccos\left\{\frac{R_E}{R_E + A}\right\}$ R_E = radius of Earth A = height of the orbit

$$T_{day} = \frac{180° + 2\alpha}{360°} \qquad T_{night} = \frac{180° - 2\alpha}{360°}$$

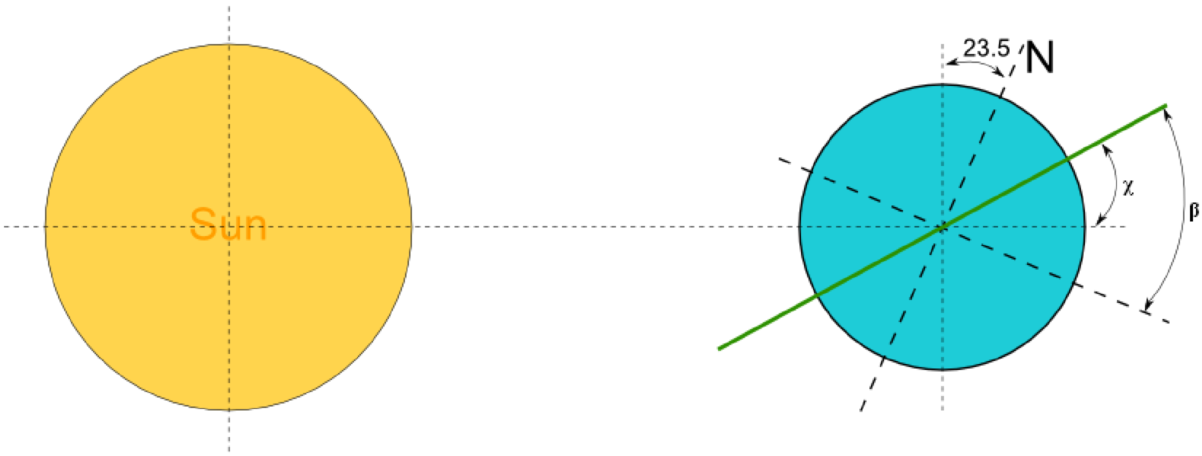


An α angle affects length of night and day zone. Now there are conversations about solar-synchronized orbits on heights 600km and 700km. For this orbits length of day and night zone is T_{day}=64% iT_{night}=36%.

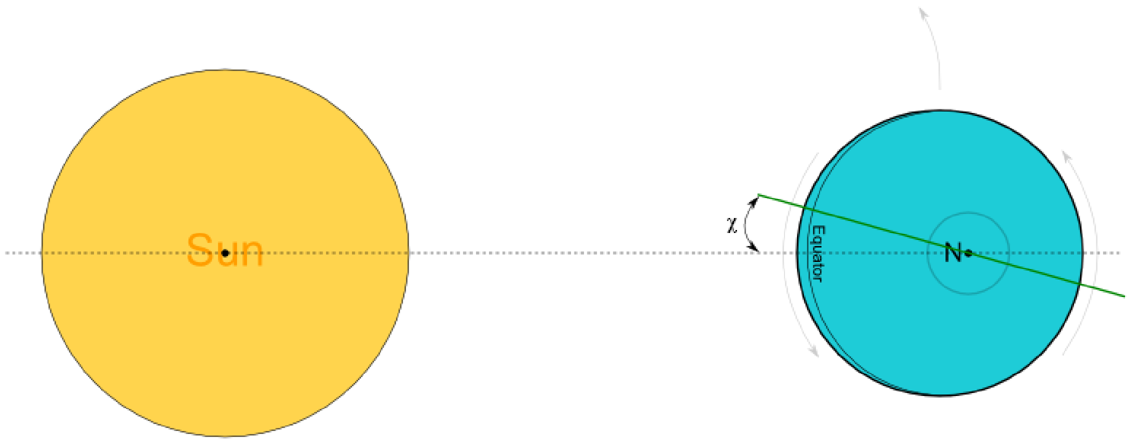
4.2.2 Orientation of an orbit to the Sun

Pictures below show determination of angle of incidence. It is necessary because of angle incidence on a panels.

The angle χ=β-23,5° determines orientation of the orbit (inclined from the equator by appropriate angle) relative to solar rays:



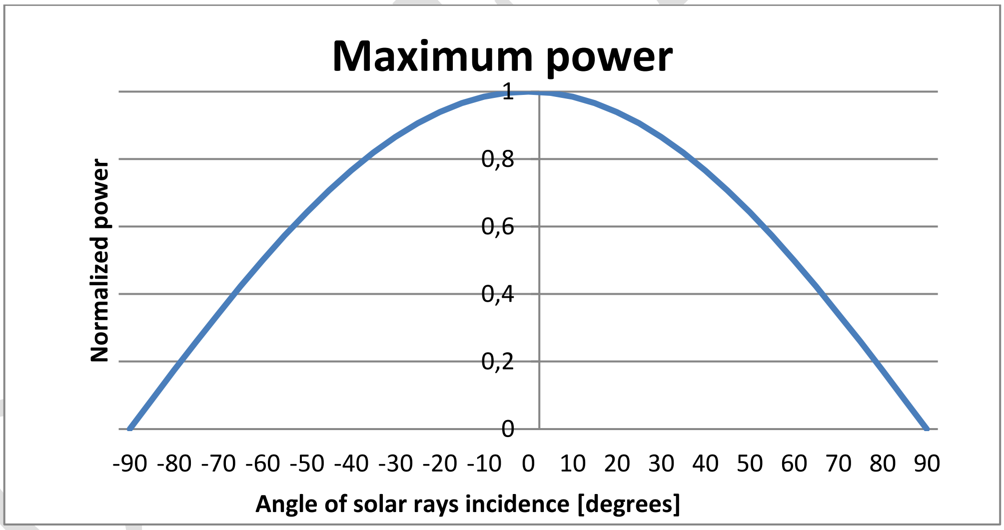
In a picture below an orientation relative to solar rays is determined:



To simplify, 1st or 2nd way of determining the angle will be applied. For the solar-synchronized orbit the 2nd picture will be applied, so that the simple way of calculating an angle between orbit surface and solar rays could be used.

4.2.3 Power of solar panels depending on angle of light

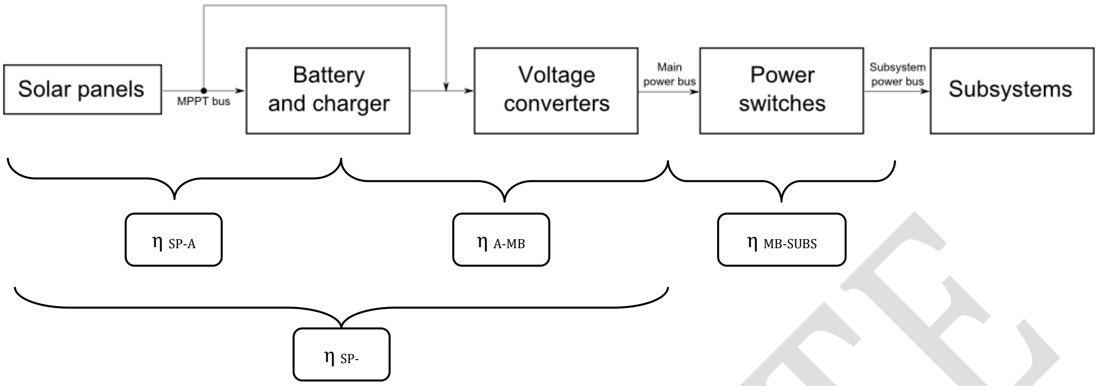
Power obtained from solar panels depends on the angle of incidence of solar rays. The biggest power can be obtained when solar rays are given perpendicularly.



A plot above presents theoretical dependence between power and angle of solar rays given to solar panels.

4.2.4 Efficiency of power processing

Each block of power system has its own efficiency. Energy from solar panels can charge accumulators or supply subsystems directly. Subsystems can take energy from accumulators. Before main bus of supply there are set of converters that adjusts inside voltages of EPS to subsystems requirements. Then it should be keys that turn voltages on/off to needed subsystems.



P Approximate efficiencies of every path of power processing are shown on a table below.

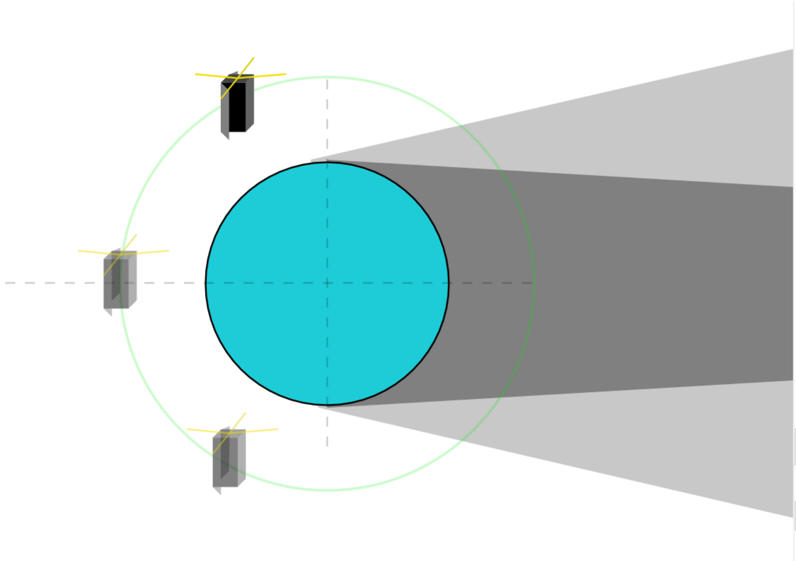
Path of power processing	Efficiency	Designation
From solar panels to accumulators	80%	η_{SP-A}
From solar panels to supply bus directly	70%	η_{SP-MB}
From accumulator to power bus	85%	η_{A-MB}
From main supply bus, via keys, to podsystems	99%	$\eta_{MB-SUBS}$
Error of MPTT algorithm	5%	ERR_{MPPT}
Error of ADCS tracking sun	10%	ERR_{F-ADCS}

4.2.5 CALCULATING POWER OBTAINED ON AN ORBIT

Obtained power depends on angle of solar rays, and that depends on satellite orientation. We concerned 3 cases: tracking the Sun by ADCS subsystem, tracking the Earth and working with ADCS turned off. Time of the orbit is accepted on 90 minutes = 5400s.

Tracking the Sun

Sun tracking is available because of special mode in ADCS subsystem. The system is correcting the orientation so that solar panels are facing the sun.



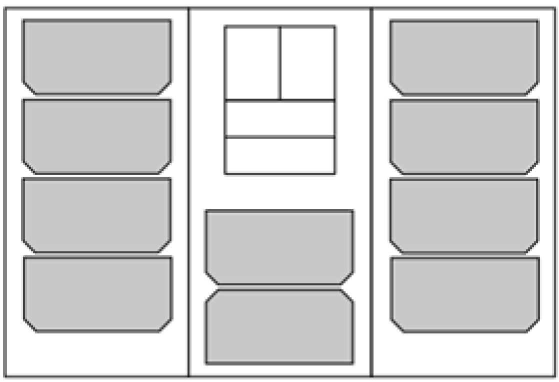
If tracking success during whole flight in a day zone, theoretically average power from panels is:

[soefficient_day_zone]*[time_orbiting_in_seconds]*[power_from_solar_panels] = [energy_obtained_from_1_orbit]

$$T_{day} * T_{orbit}[s] * P_{sol}\ [W] = E_{orbit}\ [Ws]$$

If satellite tracks the sun by setting main panels, theoretically maximum power is P=10W. When calculating power we should consider algorithm error MPPT from converters in supply system and errors from ADCS tracking Sun algorithm.

$$P_{Sol} = (1-ERR_{MPPT}) * (1-ERR_{F-ADCS}) * P = (1-0,05) * (1- 0,1) * 10W = 9,4W$$



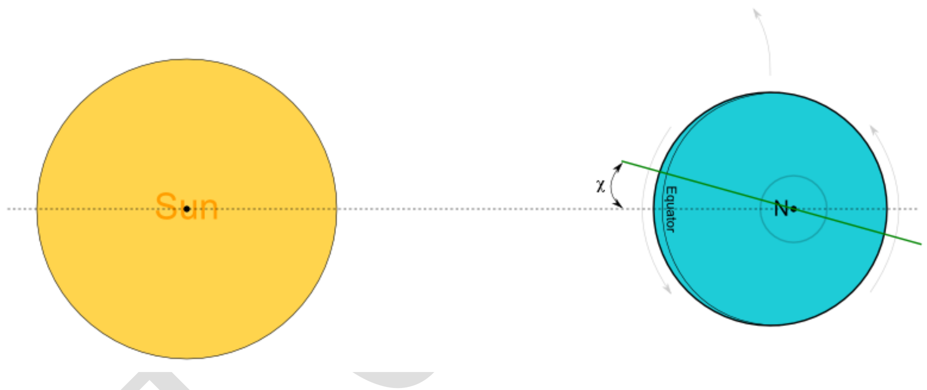
$$E_{orbit} = 0,64 * 5400 *9,4W = 32486\ Ws = \sim 9Wh$$

The result above is rounded to 9Wh. Power obtained in that way is mainly depending on power consumed by ADCS subsystem, its precision and efficiency of power processing bocks in EPS.

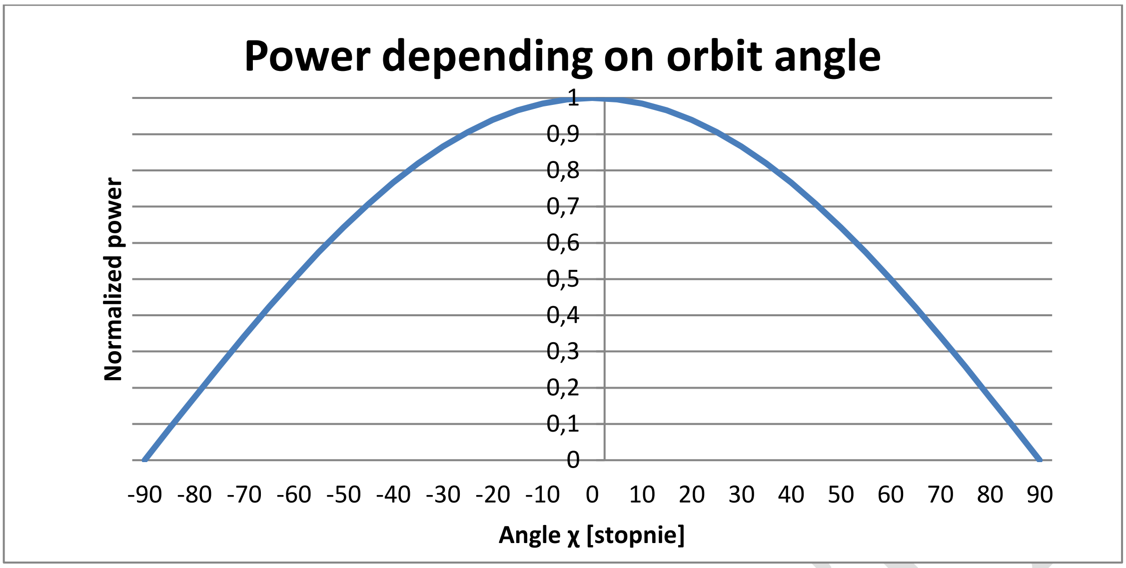
Camera directed to the Earth.

When a camera will be directed to the Earth during whole day zone, solar rays will incident from different angles, depending on the satellite localization. Then, orientation related to the Sun depends on orbit, so energy obtained from 1 orbit is dependent too.

At the point below there are considered solar panels located only in one side of the wing. Panels located on the other side will be directed to the Earth, so it will be lightened up only if we reach out 90 degrees angle relative to solar rays. According to the fact, they will be lightened up for a very short time and very big angle,, which will generate very small amounts of energy.

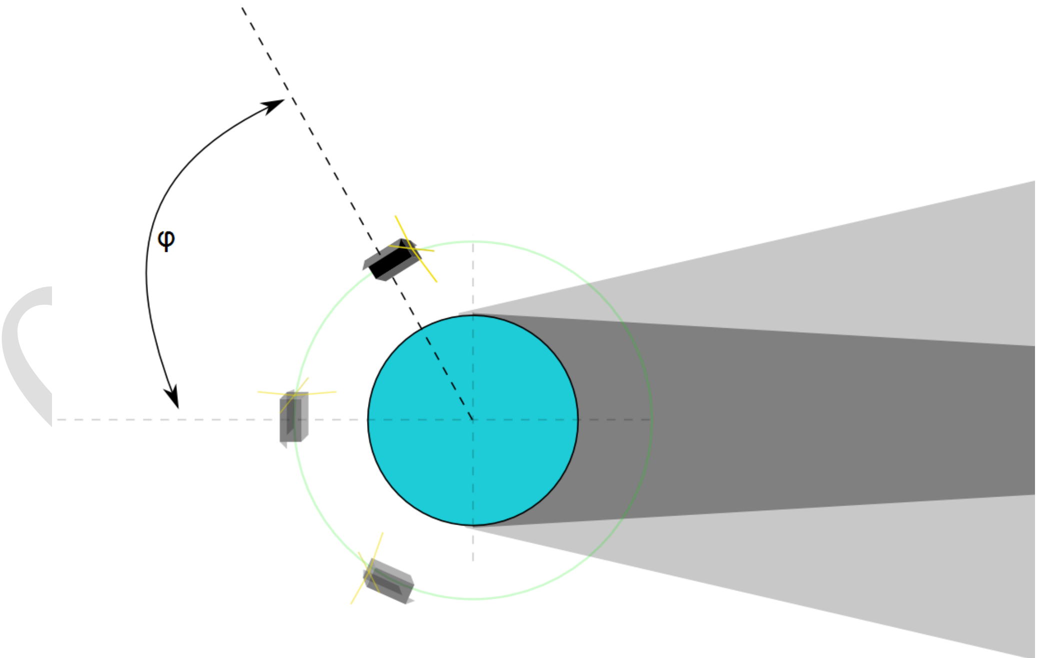


Generated power depends on location of satellite orbit. The chart below shows approximately maximal power depending on angle of orbit χ.

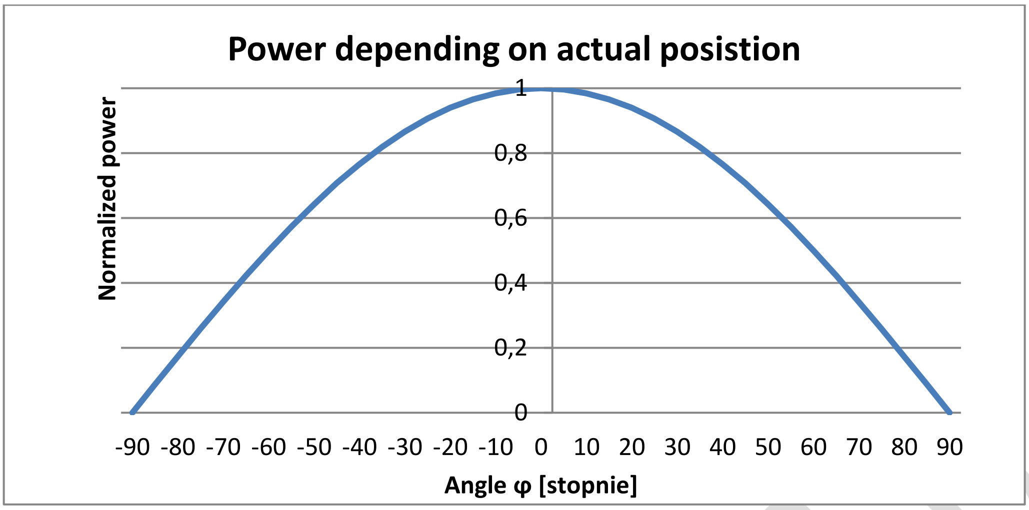


For polar orbit, solar synchronized 10° value of angle will be adopted. It gives normalized value of power 0,98 of nominal power of solar panels. For panels built from photovoltanic cells with efficiency of 30% and power of 1W, maximum power to be obtained is 0,98W.

The energy depends on **χ** angle, which determines optimal angle of solar rays that is possible on each orbit. In addition to this, actual related to Sun position(that changes in time) affects the angle too.



Angle **φ**changes over time. The relation can be approximately described by cosine (without considering solar panels on the other side of wings):



Power from solar panels surfaces located on one side of a wing is possible to receive in the range of **φ** angle between -90° and 90°. Beyond these values solar panels are shadowed and do not generate any power. The dependence below show calculation of energy collected during 1 orbit coefficient:

$$\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos(\varphi)\, d\varphi = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos(\varphi)\, d\varphi = sin(\varphi) \Big|_{-\frac{\pi}{2}}^{\frac{\pi}{2}} = 1 - (-1) = 2$$

Rectangular window from -90° to 90° is π[units^2] when the Sun is tracked propely by ADCS . At this time, when Sun tracking , we could achieve an Energy of:

$E_{-90\,90^\circ}$ = (T_{orbity}[s] / 2) * P_{sol} = (5400s/2) * 10W * 0,98 = 7,3Wh

If a camera is directed to the Earth, energy coefficient incidenting solar panels is:

$\frac{2}{\pi}$ = 0,634

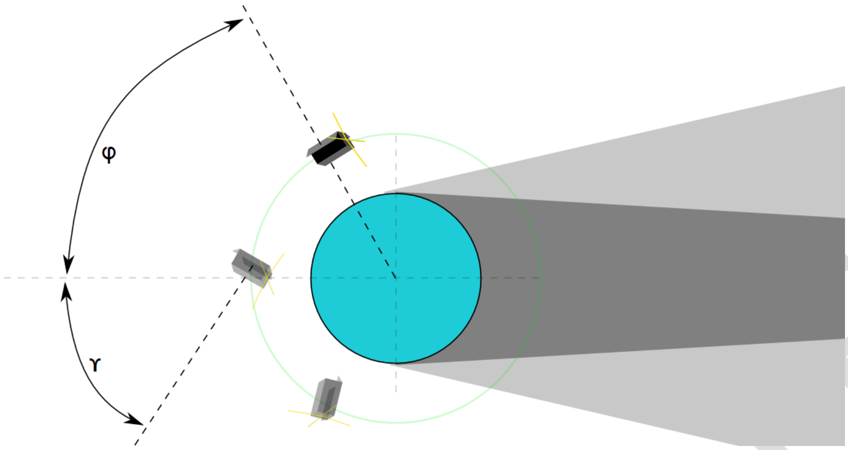
And energy obtained is:

E = $E_{-90\,90^\circ}$ * 0,634 = 4,6Wh ~ 4Wh

The value above is 2 times lower than a value when a satellite tracks the sun by solar panels. The vaue above will be rounded to 4Wh.

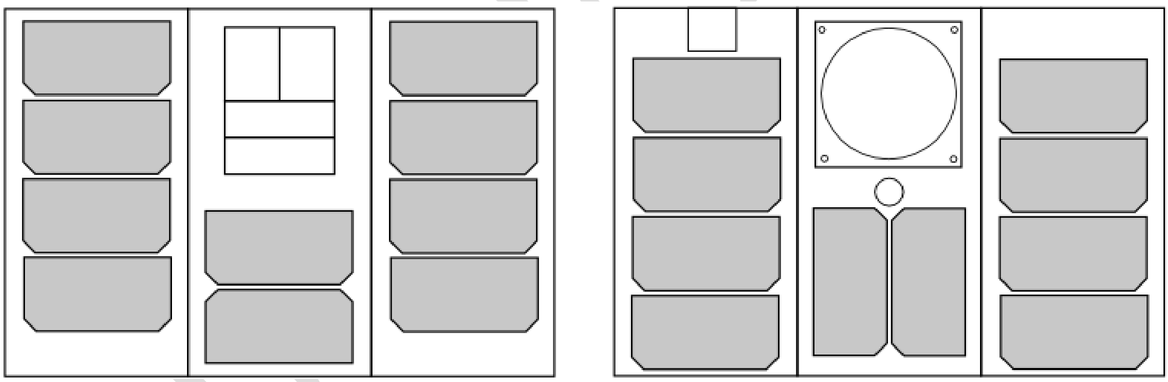
Uncontrolled satellite rotation

At this section the case when satellite is rotating without any control happens, for example when ADCS subsystem will fail to run. The period of satellite rotation is much more longer that a period of orbiting the Earth. At this point we should consider also panels located on the other side of wings.

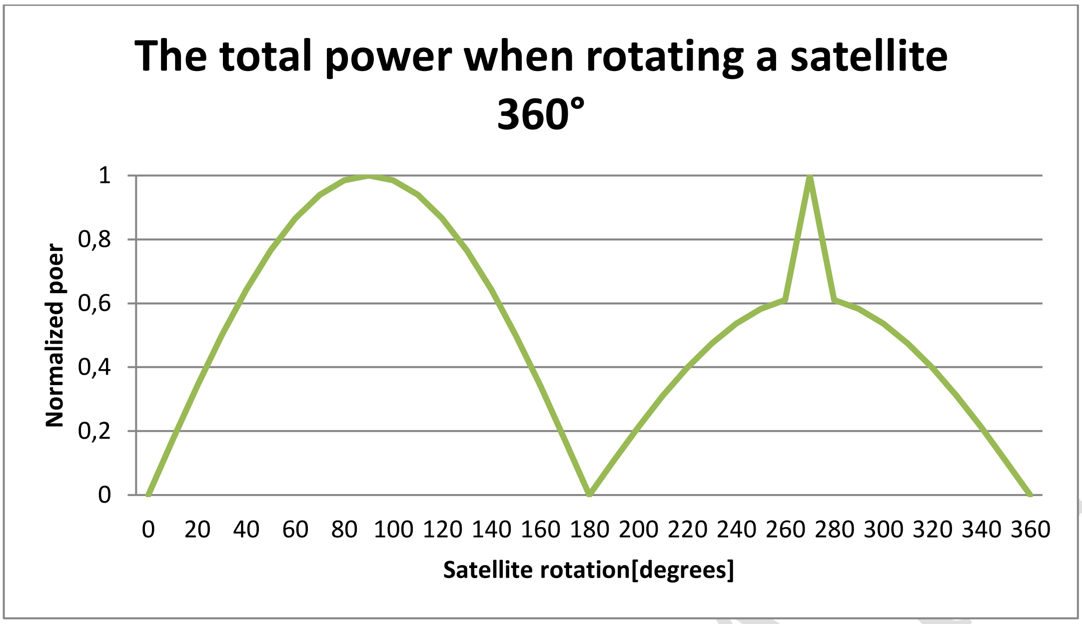


Direction of solar rays and optimal angles for solar panels(perpendicular to its surface) are marked above. Change of orientation of a satellite causes a change of these angles, so generating power changes over time.

Both sides of a satellite there are 20 photovoltanic cells:



To simplify it is adopted that maximum power from panels of each side is 10W. Because of that, we could adopt previous calculations about rotating a satellite from 90° to 90° relative to the Sun cause a change of generated power. That's why solar panels are located on opposite sides – every time there's one side lightened up. The chart below shows rotation of a satellite with an angle of 360° and its dependence on generated power:



On the plot above, in a right side there is a result of blocking of solar panels by the shadow. Satellite is rotating, which cause a shadow on one of wings. A characteristic peak of power is caused because at one moment all panels on one side is oriented perpendicularly to the solar rays. It is not considered in the calculations below.

Average power on one roation of a satellite (simplified – without power peak)

$$P_{average} = \frac{\left(\frac{2}{\pi} * 10W\right) + \left(\frac{2}{\pi} * 10W * 0{,}63\right)}{2} = 5{,}2W \sim 5W$$

<u>When uncontrolled rotation of a satellite occurs, the average power obtained from all solar panels is 5W.</u>

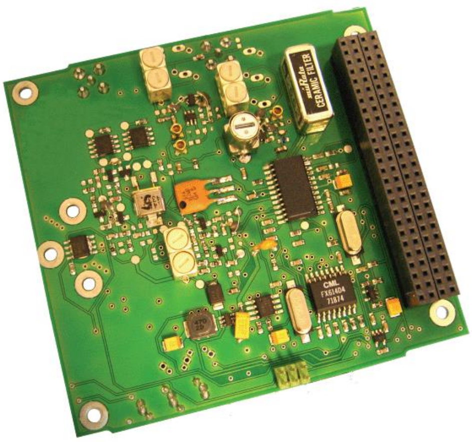
4.3 Power consumed by each module

Analysis fulfilled below refers to commercially modules and it concerns consumed power. It will provide information for further sections – selection of appropriate accumulators and projecting approximate budget of power.

Communication module UHF/VHF

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

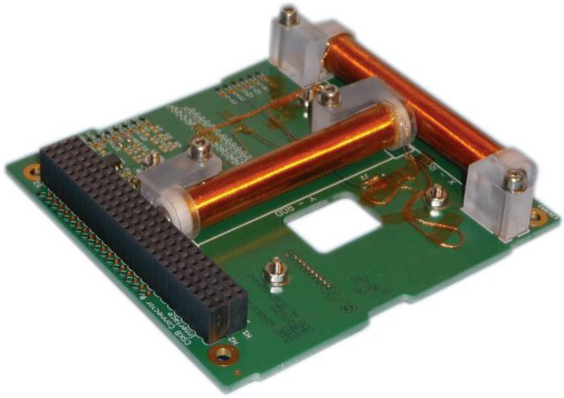
There were conversations with manufacturers of communication UHF/VHF modules. „ISIS VHF downlink / UHF uplink Full Duplex Transceiver" was chosen:



It uses interface I^2C to communicate.

Attitude Determination and Control System (ADCS)

Name	Power consumption in detubling mode	Power consumption when keeping the orientation	Power supply
ISIS Magnetorquer Board	<2,0W	<1,0W	Actuators: 5V Elektronics: 3,3V



The module communicates via I2C interface. Calculations about position and other controllers take place at OBC.

On-board computer

Power consumed by a computer in normal mode (all peripherals on) is <1W (according to data from CubeComputerV3 computer from ESL, the computermeets the requirements of mission PW-Sat2), and in sleep mode <0.1W. These are approximate values which will be taken to further analysis.

Camera CAM2

Camera CAM2 located in a prototype Kamera CAM2 umieszczona w prototypie:

Matrice 1/6", resolution: 640x480, power 300mW, frames per second: do 30, dimensions: 6x6x4.5mm, interface I²C.

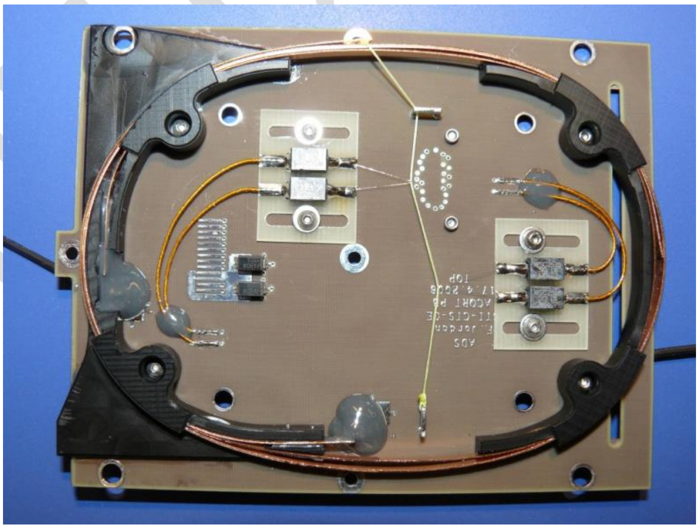
Payload electronics

Electronics of payload include: electronics of camera and Sun sensor. To further analysis it will be assumed that electronics of camera control can consume up to 0.5W, and Sun sensor 1W.

System of Dyneema cords burn-out

Dyneemastrings are widely used in satellite technique in releasing mechanisms. High durability makes them possible to hold the mechanism before realising. After burning the Dyneema cord out, something deploy, e.g. solar cells, deployable antennas or deorbitation structures. Force needed to open any system is usually obtained from different types of springs, held by Dyneema cords.

System that was used in SwissCube:



We assumed, that for every knob burned out by thermal knife is reserved 0.5W. The power is being took for maximum 30s, to the moment of burnout of the Dyneema cord. We also assumed, that number of all knobs is 10, so maximum power consumed simultaneously is 5W.

Maximal power consumptions for each subsystem

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 to 30s Normal work: <20mW (supply of sensors)
BATTERY	Accumulator package	Accumulator	Heating: 1W in shadow zone
EPS	Supply system	Inside	Sleep mode: <0,1W
SADS	System of opening solar panels	6.5-9V	Opening panels: 2W during 30s
Sail	Sail– deorbitation system	6.5-9V	Opening deorbitation structure: 2W during 30s
ADCS	System of orientation changing –actuator modules with PWM drivers	3.3V 5V	Supply for sensors and electronics: <0.5W Actuators supply: <1.5W
PLD	Payload electronics	3.3V 5V 5V 6.5-9V	Cameras: CAM1 1W, CAM2 0,3W SunS: 1W Photodiodes: 0.5W Camera heaters: CAM1 1W, CAM2 1W
MAGNETOMETER	Magnetometer	3.3V	One magnetometer: 100mW Redundancy of magnetometers – can be more than one
OBC	On-board computer	3.3V 5V	Main - processing: <1.5W Main – sleep mode: 0.1W Reserve - processing: 0.2W Reserve – sleep mode: <0.05W

4.4 Accumulators

We've chosen NanoPower BP4 from GOMSpace company package of accumulators:

The package includes 4 Li-Ion accumulators. Every connection between the accumulators is possible. Package includes built-in control and temperature control system. Capacity of the package is 40wh. Price about 1500€.

GomSpace 18650 battery with heater element

According to GOMSpacedocumentation, accumulators lose 20% capacity after 350 cycles of charging:

3.7V batteries

DOD	80% remaining capacity 25 degC, +1C/-1C, 4.2V EOCV	65% remaining capacity 25 degC, +1C/-1C, 4.2V EOCV
100%	350	430
50%	1000	1200
25%	1700	2100

Considering above, we should design power budget in that way, so that in most cases discharge of the accumulators would not be more than 25%. When having a package with capacity of 40Wh, we should use only 10Wh of capacity. It will allow the package to last longer on the orbit.

4.5 Energy available on orbit

Maximum possible energy from solar panels from one orbit was calculated above. It depends on a state on which satellite is. There was analysis on the following cases: ADCS is tracking the Sun to have maximal power, camera is directed to the Earth, rotating without any control.

Satellite state	Energy obtained from solar panels in one orbit
ADCS is tracking the Sun to have maximal power	9Wh
Camera is directed to the Earth	4Wh
Rotating without any control	5Wh

Values above do not include power needed to heat elements and power consumption of EPS and computer in sleep mode.

Energy needed to keep basic functions of a satellite during charging accumulators, in sleep mode and without any control. This mode will be activated in moments, when the satellite is waiting for the next task or command. Values above are related to one orbit.

Energy consumer	Power requisition
Accumulators heating	0,5Wh
Heating other elements	0,5Wh
OBC sleep mode	0,15Wh
EPS sleep mode	0,15Wh
Communication module in receiving mode	0,3Wh
	All: 1,6Wh

Energy keeped in the accumulators during one orbit (considering a path from solar panels to accumulators):

Satellite state	Stored energy considering efficiency of EPS paths
ADCS is tracking the Sun to have maximal power	7,2Wh
Camera is directed to the Earth	3,2Wh
Rotating without any control	4Wh

After subtraction of energy requisition for basic satellite functions, we have:

Satellite state	Stored energy considering efficiency of EPS paths, available for subsystems
ADCS is tracking the Sun to have maximal power	4,7Wh
Camera is directed to the Earth	1,3Wh
Rotating without any control	2Wh

4.6 CHARGING AND DISCHARGING ACCUMULATORS

Battery life of Lithium-ion batteries depend on their discharge. Depth-Of-Discharge coefficient (DOD) 25% allow to 1700 cycles of charge (according to GOMSpace documentation) with capacity loose about 80%. With orbits of 90 minutes duration accumulator should keep its nominal capacity above 80% during couple of months after start.

While designing a supply module we will apply the principle of discharging the accumulators with DOD 25%. This implies that accumulators with capacity of 40Wh will be treated like a accumulator with capacity of 10Wh.

Time of accumulators charging

From previous analysis we know that maximum value of stored energy om one orbit is 4,7Wh, and minimum 1,3wH. It is an energy stored in accumulators, which is available for subsystems (considering loss and basic needs of OBS, EPS and communication).

If subsystems consume 10Wh, time of charge will be from 8 orbits(12hours) to 3 orbits (4,5 hours).

4.7 Budget of available power

In order to keep safety margin of power, mission will be planned in a way to not to use more that 10Wh during 24h. Thus, the satellite will be provided with energy for basic functions. If power budget turns out to be greater than the worst case, additional tasks would be done.

4.8 Bibliography of power budget calculations

1. "Instantaneous Power Calculations in Matlab for ICARUS" - Conrad J. DeWitte - University of Michigan 1999.

2. "Power Budgets for Mission Success" - Craig Clark and Ritchie Logan – ClydeSpace 28 April 2011.

3. "FAST PROTOTYPING: A CASE STUDY THE JPEG COMPRESSION ALGORITHM" - S.PILLEMENT, L.TORRES, M.ROBERT and G.CAMBON

4. "Plotting the Orbit of a Planet Using Excel" - Michael Fowler

5. "DIY Satellite Platforms" – Sandy Antunes – Project Book 2012

6. "Power budget" http://www.lr.tudelft.nl/en/organisation/departments/space-engineering/space-systems-engineering/expertise-areas/spacecraft-engineering/design-and-analysis/subsystems/electric-power/power-budget/ - B.T.C. Zandbergen - 19 September 2001

5 POWER BUDGET AFTER RELEASING FROM P-POD

After releasing from P-POD, EPS turns on. After that, OBC turns on and have its memory tested. Then ADCS is tuned on, in order to stop uncontrolled rotations of a satellite. After half an hour the earliest, it's possible to open the antennas, but only after slowing down of uncontrolled rotations. Depth-Of-Discharge coefficient of accumulators is 25%, co its required not to overcome value 10Wh of power consumption.

Values above refer to detumbling process:

Task	**Maximal duaration**	**Power consumption**	**Energy requisition**
Turing on OBC and memory testing	0,5h	1,5W	0,75Wh
OBC sleep mode – waiting for next command	1h	0,1W	0,1Wh
ADCS in detumbling mode	5h	2W	10Wh
Opening antennas	30s	5W	<0,1Wh
Communication module in receiving mode	1h	0,2W	0,2Wh
Testing other subsystems	1h	Average 2W	2Wh
			13,12Wh

The process od testing and work preparing uses minimum 13,12wh of energy from accumulators. We do not consider energy, which could generate solar panels during this process

6 BALANCE OF TASKS POWER

Each of task require some amount of energy. It is measure in watt-hours (Wh). It makes the planning easier and objective according to energy in accumulators. Requisition for basic functions of a satellite was calculated above. In this section we do concern energy requisition for subsystems.

Some tasks will be critical, it means necessary for fulfil the while mission, some of them will be optional, depending on the power and communication budget.

6.1 TAKING AND SENDING CAM2 PHOTO

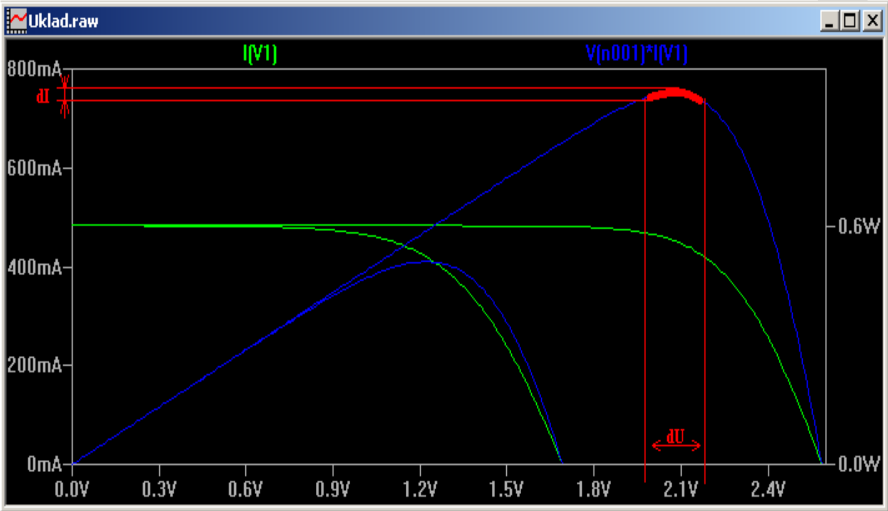
To make a photo with CAM2 you have to turn on CAM2 and OBC. In this moment, communication module is in receiving mode. If the photo is made and saved in memory of OBC, it should be sent to the Earth.

Task	**Power requisition**
OBC working at receiving single image from CAM2 and processing it send	0,5Wh
ADCS stabilizing	1Wh
Camera working	0,2Wh
Sending to the Earth	1Wh
Keeping the orientation	1Wh
	2,7Wh

The analysis above shows that taking one photo from CAM2 and sending it to the Earth will consume about 3Wh of energy. In further phases of the project this analysis will be developed. Furthermore, other tasks will be described in that way.

7 PROTOTYPE OF MODULE MPPT 1V0

Module of pulse converter MPPT searches for maximal point of power from solar cells. It works by changing the voltage, so also the current and load of each cell. Change of load causes movements of power operating point on power characteristics left or right. Movements are shown on the picture below:

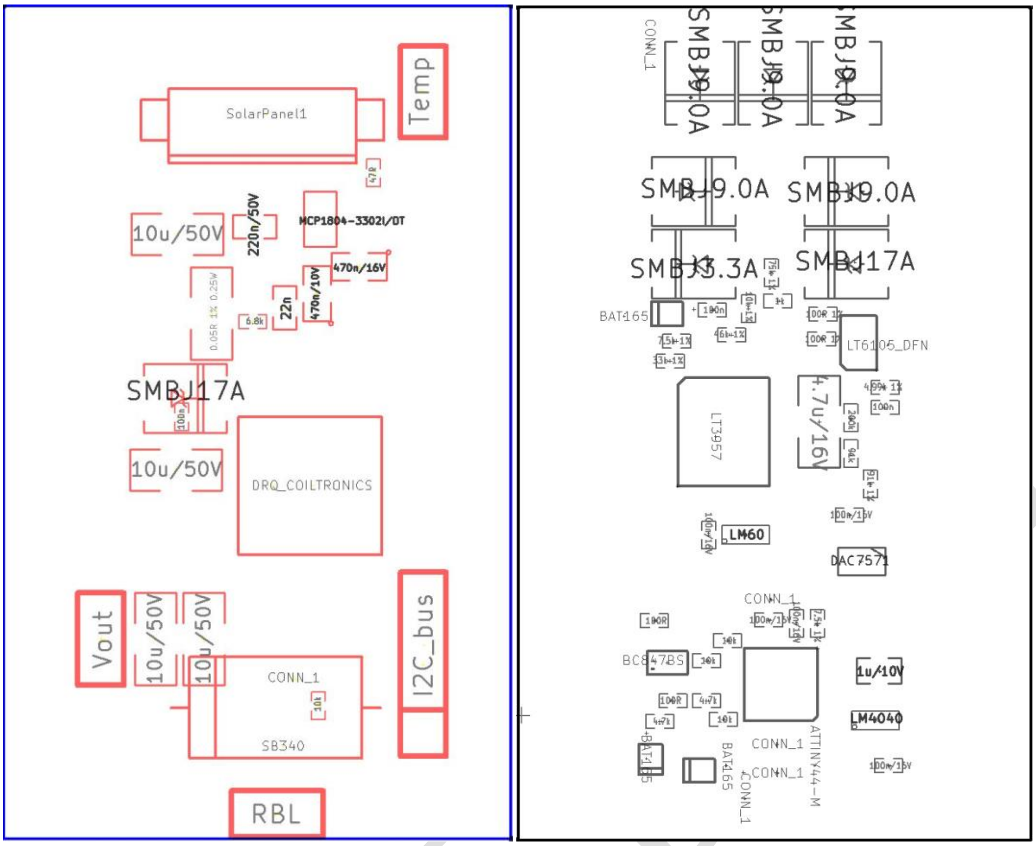


Blue lines show power characteristics in different temperatures (right- 25 °C, left - 100°C). Power obtained from solar panels depend on many factors, temperature, angle of solar rays, load etc. In order to gain maximum possible power, we needa module that track changes of power and react properly with changes of load.

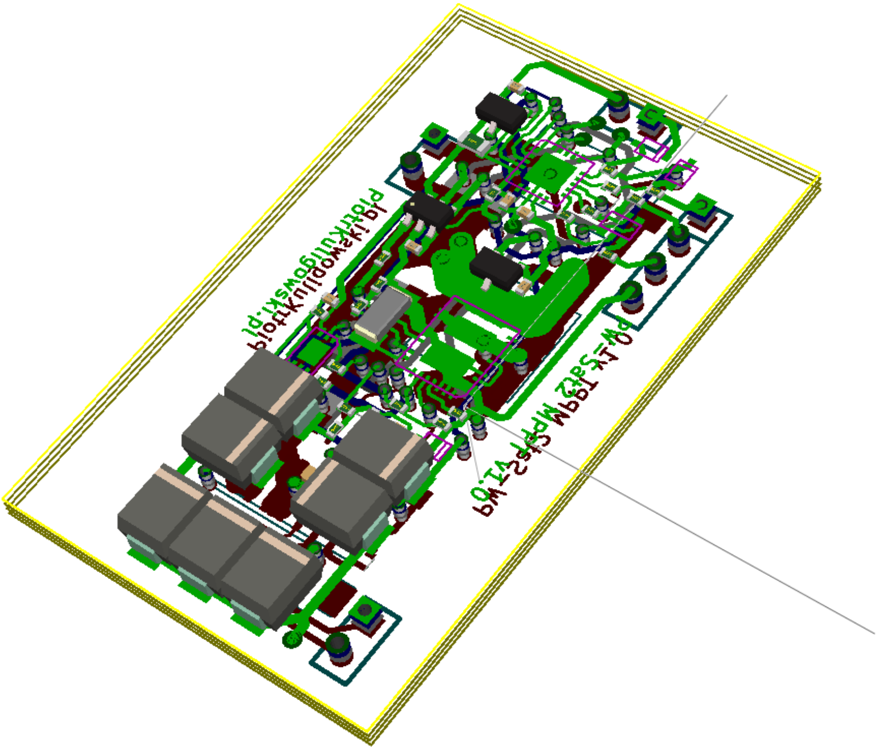
7.1.1 TECHNICAL WARNINGS ABOUT PCB

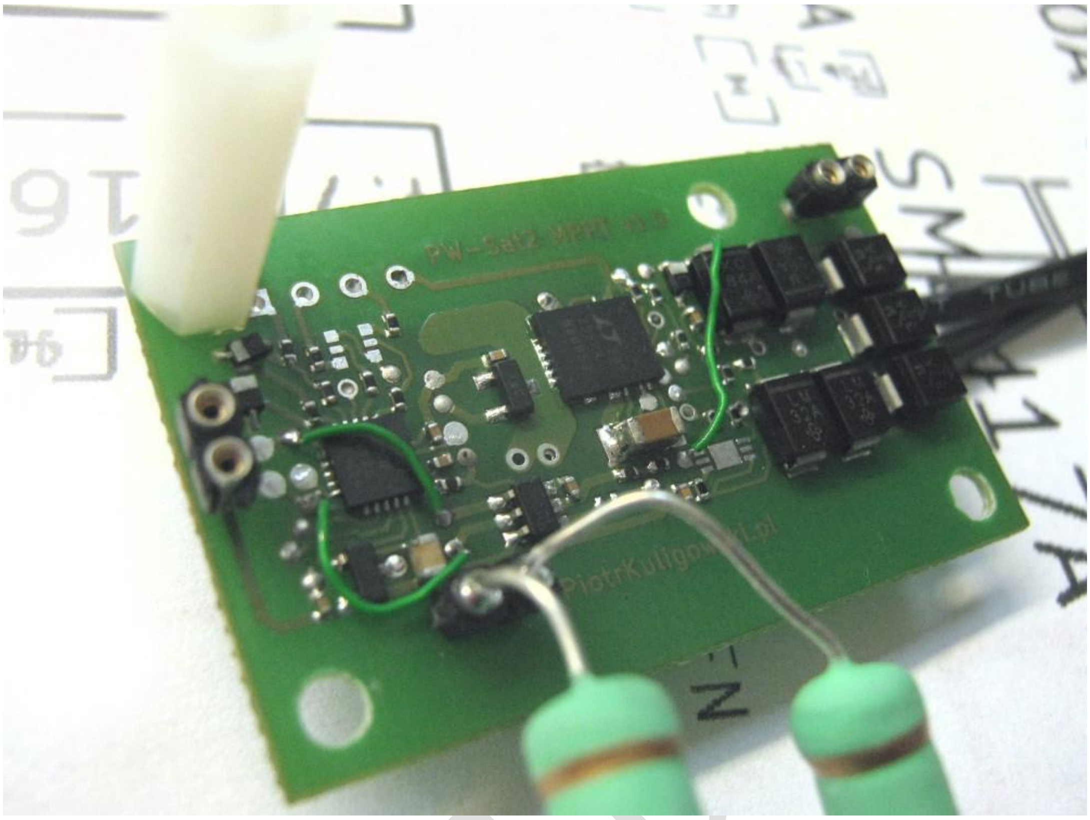
PCB was designed as 4-laer. 2-layer PCB was ordered and inside connections was made by KYNAR wires. It reduced costs of a prototype.

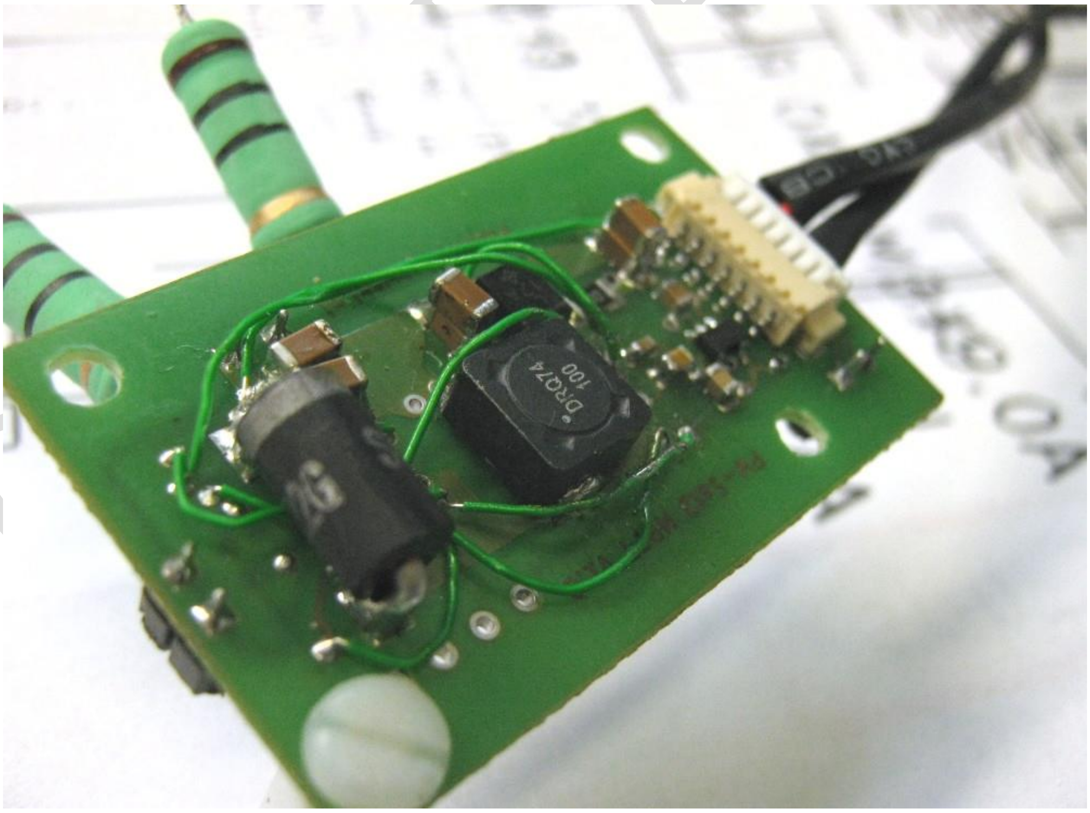
7.2 SKETCHES AND PHOTOS OF EPS PCB PROTOTYPE



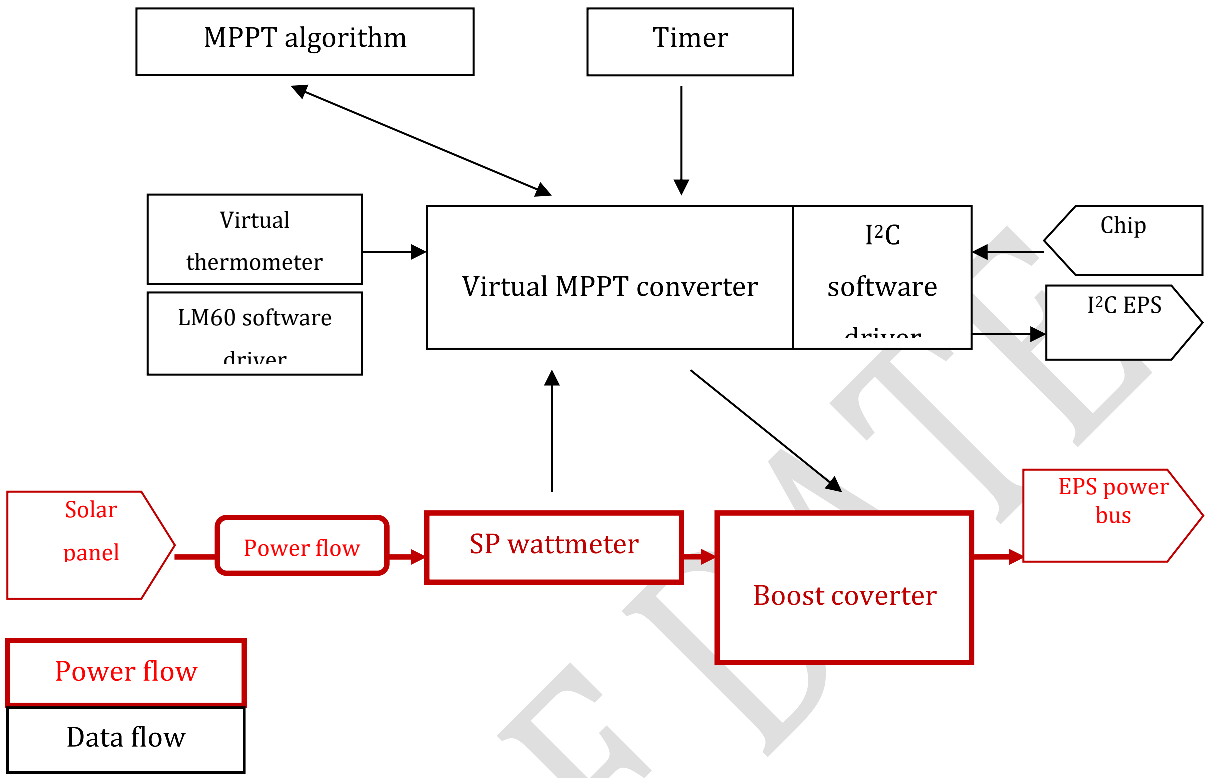
SolarPanel1
Temp
10u/50V
220n/50V
MCP1804-3302I/DT
470n/16V
470n/10V
22n
6.8k
SMBJ17A
10u/50V
DRQ_COILTRONICS
Vout
10u/50V
10u/50V
CONN_1
SB340
I2C_bus
RBL
SMBJ9.0A
SMBJ9.0A
SMBJ5.3A
SMBJ17A
BAT165
LT6105_DFN
LT3957
4.7u/16V
LM60
DAC7571
1u/10V
LM4040
CONN_1




PW-Sat2 MPPT


DRQ74
100

7.3 Block diagram of the module



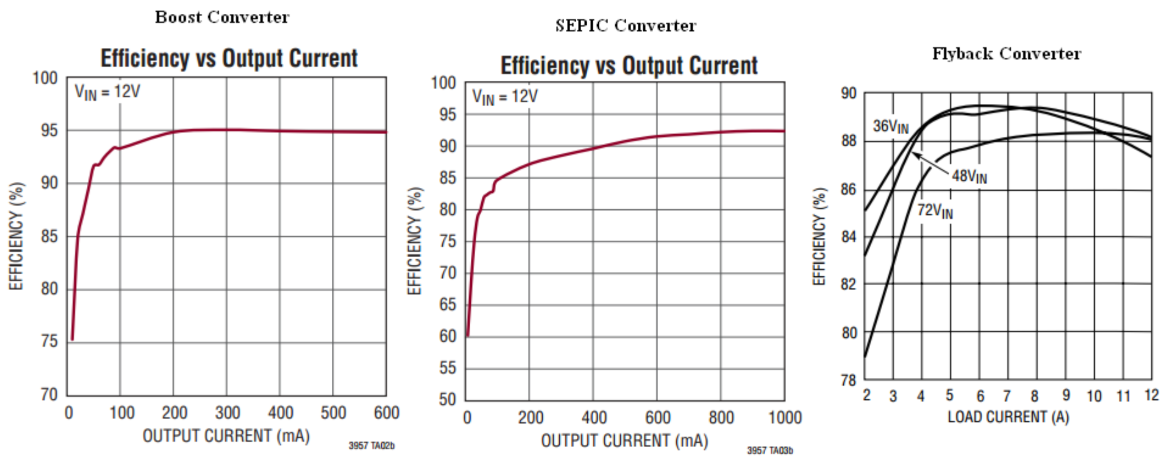
By dividing the pulse converter into blocks, as showed above,you can organise source code of a microcontroller controlling the converter. Virtual blocks represents high level functions, they do not have access to hardware level.

Boost type converter converter(step-up, so increasing voltage) is a main processing device of this module. Their output voltage is controlled by microcontroller, which calculates derivative from power from solar panels in real-time. On this basis the algorithm MPPT is controlling movements of operating point on power characteristics. The thing, that generated power depends on value of load is characteristic for solar cells. Pulse converter controls the load actively to keep maximum power.

The converter increases value of voltage to about 20V, which is much more greater than possible input voltage (5-15V). Boost type was applied here because of high efficiency (even 95%). Module is being under research to show which type of controlling the converter will be appropriate in charger MPPT supply module.

7.4 PULSE CONVERTER BOOST TYPE

The purpose of this converter is increasing voltage from solar panels, which is 0-15V to about 20V. In addition to that, output voltage should be controlled actively by microcontroller. Boost type was chosen because of efficiency. Other converters, e.g. SEPIC type do not have such efficiency. Dimensions and simplicity is also necessary. Fly-Back type does not meet the requirements. Comparison between efficiencies is showed below:



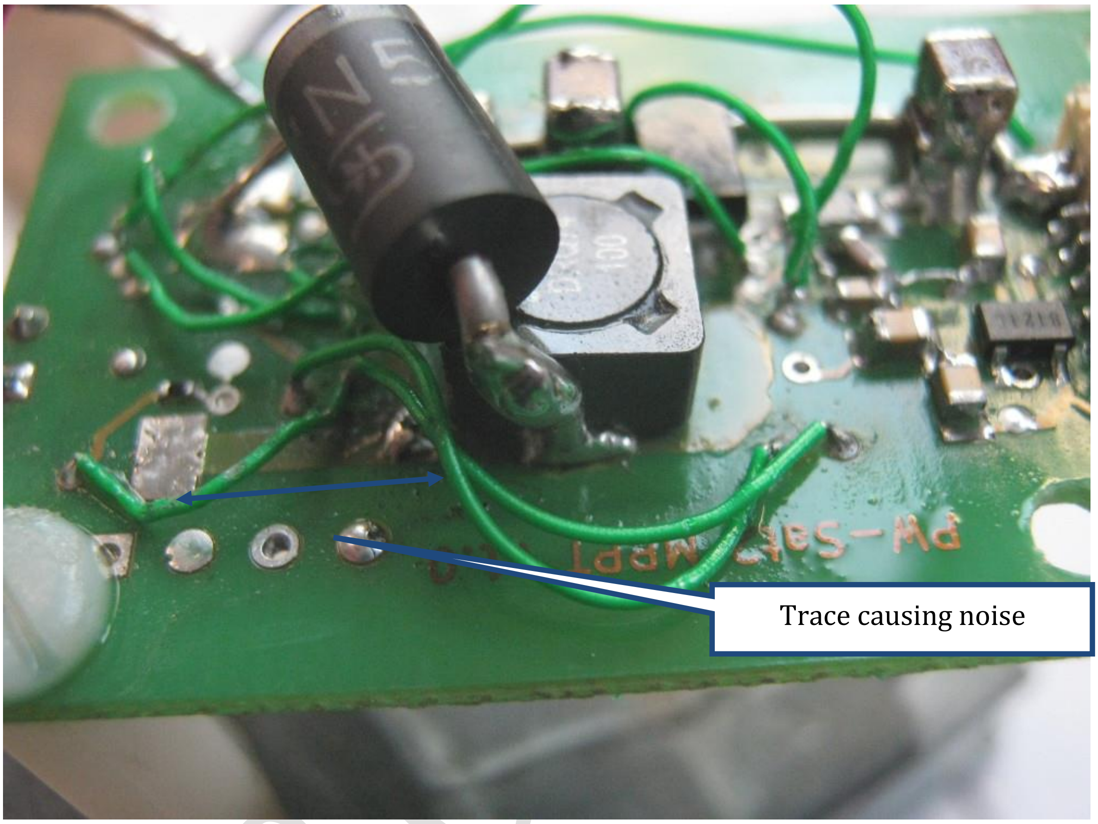
Charts of boost and SEPC type come from LT3957 catalogue, Flyback type from LT3825. Despite different currents, we could say which type would have the best efficiency. Boost type converter – increasing voltage - was chosen mainly because of efficiency and simplicity of construction. Buck type converters(decreasing voltage) has similar parameters. Although, using it the voltage would have to be decreased below 5V, o below minimum input voltage. Efficiency of the converter is very high, even 98%, but lower value of voltage require more current to transfer the same power. That would generate more heat in the traces, and it cause less efficiency of the whole system. Higher values of voltage lower the current used to transfer the same power.

Linear Technology LT3957 was chosen to work in the module. It has very small dimensions and, relative to its package, big thermal pads allowing heat dissipation to PCB. Big surface of PCB will radiate the heat.

According to manufacturer information, LT3957 in boost configuration can reach efficiency about 95%. When input power is 10W, f every MPPT converter, loss of power is 0.5W. It exhale on Schottky diode, series resistance of inductor, resistance of converter key, etc.

7.4.1 RESEARCH RESULTS

When measuring the prototype it came out, that the converter generates very high noise on the output (500mVpp) and RF noise. Purpose of this was too long trace connecting Schottky diode and inductor working with a conveter.



The problem of noise was partly solved by direct connection of diode and inductor. Noises was reduced to 100mVpp. It is a value not acceptable in a finished module. Its possible that the location of elements was not proper. On the other side of a PCB, under the inductor there are elements of the feedback loop, where could generate unexpected currents which cause non-stable work of a converter. Noise can be generated also by the KYNAR wire connections.

Despite noise problems, average voltage on the output is 19,14V, without the resistor SC_R8, which is very close to the design: 19.20V. In the module 1% resistors were used.

Some small influence in reducing noise had replacing output and input capacitors with ones with better dielectric fulfilment. Originally capacitors with Y5V dielectric was used, changed to X5R. Capacitors Y5V has very high capacity tolerance and high series resistance in high frequencies. Research about capacitors 10uF/50V with dielectric Y5V and X5R:

	Y5V	X5R

Series resistance with f=300kHz and polarization 20V	1.5Ω	0.650Ω

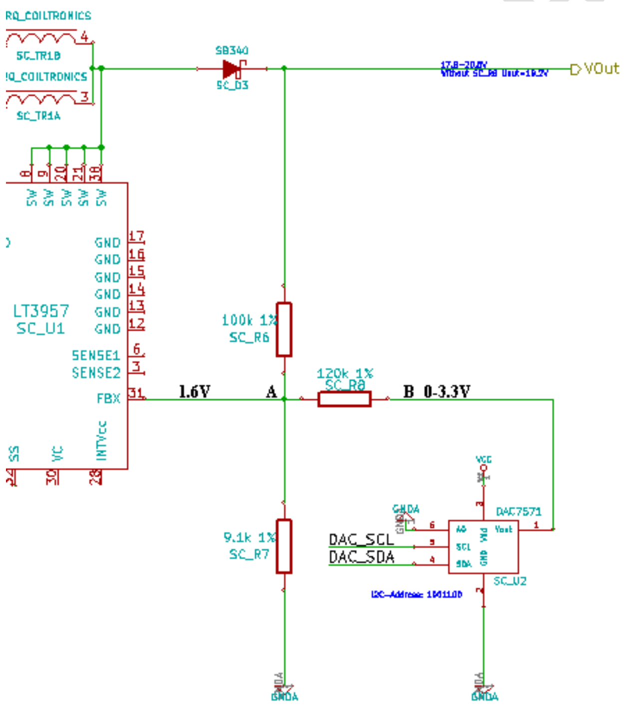
In addition to thisY5V capacitors ar very sensitive to temperature. When heated to 70°C their capacity can decrease even by 80%. A conclusion is that we should use ceramic capacitors with high capacity only with X5R or X7R dielectric. The main disadvantage of this solution is bigger dimensions than Y5V. Y5V capacitor 10uF/50V was in 1206 dimension, and the same X5R is only in 1210.

After this changes measured efficiency was 92%.

Working on reducing the noise of converter was abandoned for this prototype. New location of elements is required and will be realized in the next versions. In addition to this new, better EM-shielded inductor will be used.

7.5 Controlling output voltage

Converter is controlled by digital/analog converter, which is connected to feedback loop. Microcontroller controlling MPPT module is calculating corrections and then set appropriate value to D/A. The idea of controlling output voltage by controlling voltage of a feedback loop is showed below (elements that was unnecessary was replaced) :



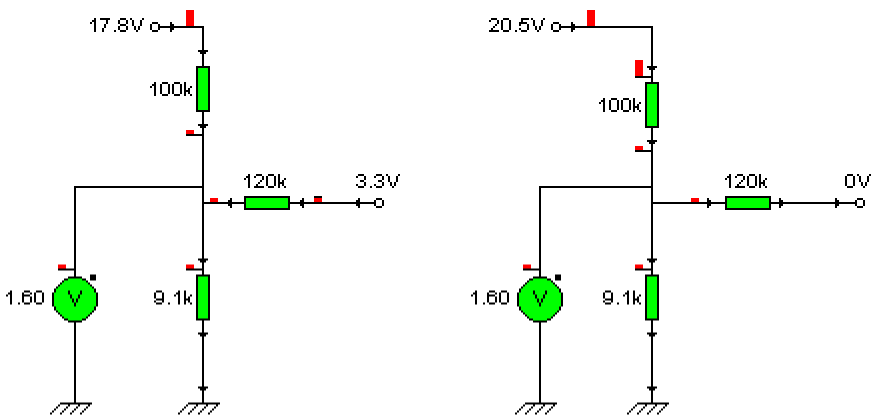
In a point described as “a” a converter tries to keep voltage value in 1.6V. It is the input of feedback loop. Resistor divider connects it with output voltage. A D/A converter after setting higher voltage, e.g. 3.3V tries to force higher voltage on feedback loop. A pulse converter do not let it and lower output voltage. For lower values of voltage, e.g. 0V a d/A converter tries to force lower voltage on feedback loop. And there analogically, pulse converter tries to prevent from it by increasing output voltage, in order to keep constant voltage 1.6V on a feedback loop.

Resistors RC_R6 and RC_R7 determine output voltage. When on D/A output 1.6V is set or when there's no SC_R8 (disconnects D/A from feedback loop), current is not flowing in or out feedback loop from D/A converter. Boost converter output voltage depends now on a formula, according to manufacturer

$$V_{OUT,POSITIVE} = 1.6V \cdot \left(1 + \frac{R2}{R1}\right)$$

For resistors from pictures above it is 19,2V. To conclude: after mounting up the prototype without SC_R8 resistor or when D/A voltage output is 0V, converter output voltage should be 19,2V.

According to the thing, that output voltage of D/A converter is 0V or 3.3V (Rail-To-Rail output OPAMP) and it connected to boo converter via 120k resistor, where SC_R7 and SC_R6 resistors are the same as on a schematic below, we can determine a range of output voltages of boost-converter:



S.C._6 and S.C._R7 determine maximum values of output voltage, and SC_R8 determine a range of voltage regulation. According to simulation above, output voltage should change between 17.8V-20.5V.

D/A converter is controlled by microcontroller via I²C. This bus is separated and used by only this module. Another I²C bus, which use transistor open-collector buffer is connected to processor controlling EPS. This solution prevents from damaging EPS processor because of converter failure, which could set too high voltage on I²C. Because of a buffer possible failures are damaging only one MPPT converter.

7.5.1 RESEARCH RESULTS

In that version D/A converter will be checked, without checking its influence on an output voltage. Too high noise makes impossible to determine the precision of output voltage changes. Research of D/A converter will allow to test I²C algorithm.

7.6 ANALOG-DIGITAL CONVERTERS

Analog-digital converters are used for currents and voltage measurements on solar panels and voltages on temperature sensors. Resolution is 10 bit, input voltage 0-2,5V, reference voltage 2.5V 0.1% (LM4040). We've used built-in converters in AVR Attiny84A controlling MPPT converters.

On every input of ADC converter is Schottky diode, preventing from too high voltage that could damage microcontroller input. RC filter averages measured value and reduces noise. Resistor voltage dividers or measure amplifiers fits input voltage level in ADC.

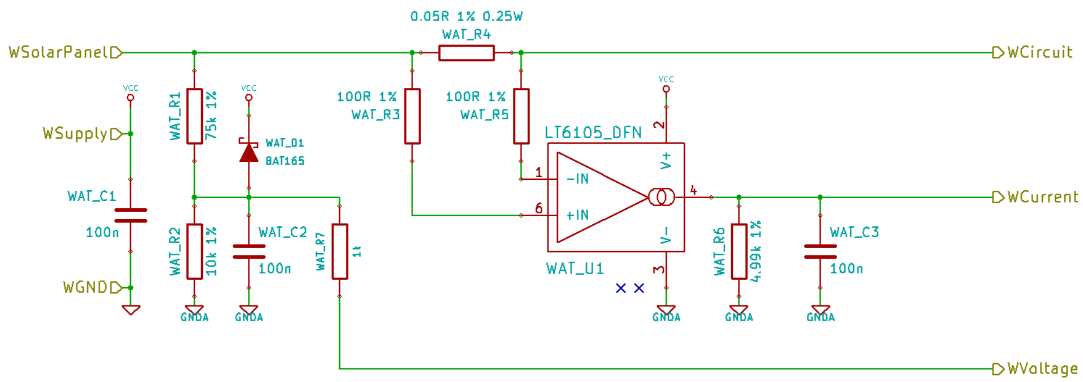
7.7 WATT POWER MET

Module of watt power meter is used for measuring power from solar panels. It provides information about power for tracking operating point on power characteristics. On the basis of the information, MPPT algorithm determine corrections of voltage regulations.

The watt power meter includes: voltage meter and current meter. Knowing current and voltage we can calculate power P:

$$P = U \cdot I$$

Voltometer include: resistor divider, RC filter and diode protecting ADC input of a microcontroller. Current meter includes: a shunt resistor, module of amplifier with current output (LT6105), RC filter and diode protecting ADC input of a microcontroller.



WAT_R4 resistor has a very low value: 0.05Ω. Amplification of current amplifier and shunt resistance are selected in that way, so measure range is up to 1A. Microcontroller reference voltage is 2.5V 0.1% (LM4040), amplification 50x, ADC has 10bit, so resolution of measure is 1mA. Range of voltage measurement when divider WAT_R1 and WAT_R2 as above is 0-22.25V with a resolution about 21mV.

Corrections of resistor tolerance should be entered in memory of a microcontroller controlling MPPT modules

7.7.1 RESEARCH RESULTS

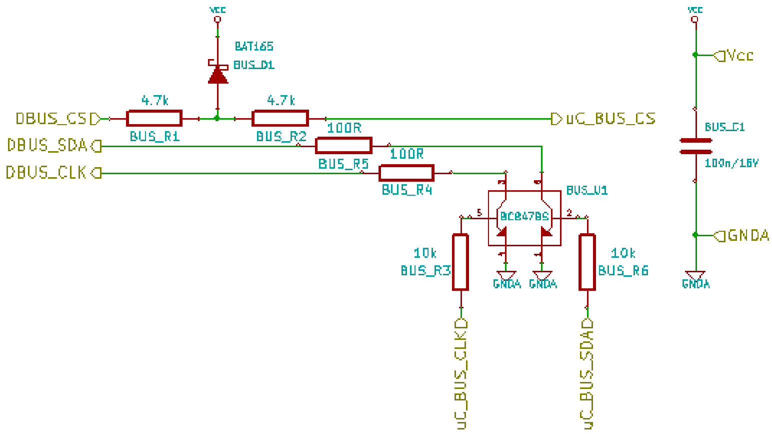
Instead of WAT_R4 resistor we've used resistor 0.047Ω (because of lack of 0.05Ω 1206 in a store), range of measure widened to 1.064A and resolution increased to 1.04mA..

7.8 I²C BUSES

In 1v0 version there are 2 I²C buses in a microcontroller controlling MPPT ATTiny84A:

Programmable, using IO ports-to communicate with an EPS microcontroller, and hardware I²C-to communicate with D/A converter.

Communication with EPS was to be realized via I²C buffer, which would separate each of MPPT converters from each other. The bus was to be one-direction with DBUS_CS(chip-select). When on the input there is a slope, MPPT microcontroller was to start transmission with an ainformation about actual state (power from solar panels, is MPPT reached, voltages, currents etc.). Buffers was NPN transistors with open emitter configuration:

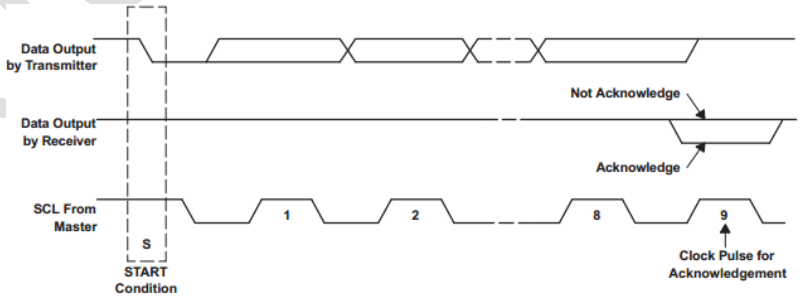


Input DBUS_CS was protected by Schottky diode from too high voltages. On lines DBUS_SDA, DBUS_SCL and SBUS was pull-up resistors (located because of the same purpose than in hardware I²C). On these lines also was transil diodes for 3.3V. BUS_R4 and BUS_R5 resistors are protecting against tensions, which are suppressed by transils.

7.8.1 Research results

I²C buses conception was changed. Corrections on PCB using external wires were made. Now, programmable I²C bus is for DAC and it is one-directional (data send only to DAC). Hardware I²C is used to communicate with EPS. These corrections will be concerned in 1v2 version. This follows from the need of bidirectional communication with EPS processor, so that programming MPPT converters is possible even during the flight.

Programmable I²C will be one-directional. Used DAC7571 converter can only receive data; one-direction bus is enough.

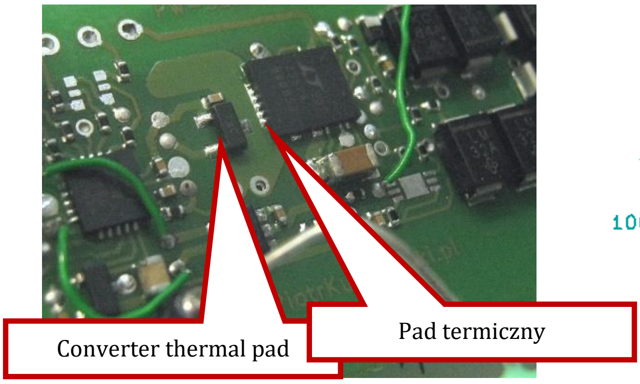


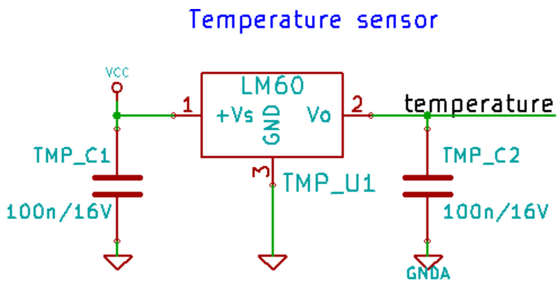
DAC7571 sends acknowledgment signals ACK. In order to prevent from shorting microcontroller PIN to the ground via transistor in DAC converter working in open-collector configuration, we need OC buffer on SDA bus. The ground short can occur, when on te output on programmable I2C is logic 1 (output of microcontroller is push-pull type) and if transistor in DAC forces logic 0 on a bus, the short to the ground and port burnout occurs. OC buffer protects from that situation.

Hardware I2C, connecting MPPT microcontroller with main computer of EPS will allow to communicate bidirectionally. As a result we will be able to change parameters of a converter without programming microcontroller. This method will shorten the process of calibration while first run (there's no need to set constants in a program). Programme of MPPT converter microcontroller will be more universal and allows us to change its parameters even when being on the orbit.

7.9 TEMPERATURE MEASUREMENT OF A PULSE CONVERTER

Converter temperature measurement is realized by locating analog LM60temperature sensor on thermal pad.





Voltage on the output of LM60 termometer is proportional to its temperature. Then, it's filtered and converted to digital in MPPT microcontroller. After reading voltage from ADC in 10-bit resolution, microcontroller calculates power with a formula from the catalogue of LM60.

Thermal pad radiates power emitted by converter. Simultaneously, LM60 measure a temperature of the pad.