NARVIK UNIVERSITY COLLEGE

HIN – Diploma
Master of Science

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The power PCB is a distributed power system based on DC/DC converters. This system distributes power at different voltage levels to the different subsystems.

The backplane acts as a motherboard in the satellite, this makes it easy to connect the subsystems and distribute the power. The backplane also contains the bus structure used by the subsystems to communicate with each other. The power management unit (PMU) is placed on the backplane. The PMU handles the housekeeping data.

The report also includes considerations on EMC, reliability and redundancy. Some sensitivity analyses of the DC/DC converters. To be able to test the system a simulator is created

Keywords:	*Norske stikkord:*
CubeSat, Power supply, Power management, Embedded system, Solar cells, Battery, Microcontroller, EMC, Reliability, DPS, Simulating, Sensitivity analysis, DC/DC	CubeSat, Strømforsyning, Strømfordelning, Innebygde system, solceller, batteri, DPS, Mikrokontroller, EMC, pålitelighet, simulering, sensitivitets analyse, DC/DC

1 Preface

This report contains a solution to a power supply/ power management system. The power supply is made of two PCB who is attached to each other. The PCB facing down is called the Power PCB and the one facing up is referred to as the Backplane.

The connectors where the subsystems should be attached are placed on the backplane. The power management unit (PMU) is placed there as well. The PMU is a microcontroller that handles the housekeeping data. The Power PCB is a Distributed Power Systems (DPS) built upon DC/DC converters.

The report is divided in two major parts. One part called "theoretical part" and the other called "practical part". The theoretical part contains studies and considerations regarding architecture, components, structure and design which the power supply is built upon. The practical part contains documentation and results on the power supply development.

There is a chapter called "developing the power supply system". This chapter is more of history then science. It contains information on some of the previous work and a resumé of the gatherings arranged by Andøya Rocket Range (ARS) and Norwegian Space Center.

There are some people we want to thank for supporting us on our work on this diploma:

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4 Abstract

The power supply system on board the satellite consists of three major parts; solar cells, battery and the power management system. The power management system is made of two different PCBs, the backplane and the power PCB.

The power PCB is a distributed power system based on DC/DC converters. This system distributes power at different voltage levels to the different subsystems.

The backplane acts as a motherboard in the satellite, this makes it easy to connect the subsystems and distribute the power. The backplane also contains the bus structure used by the subsystems to communicate with each other. The power management unit (PMU) is placed on the backplane. The PMU controls the use of power as well as handling the housekeeping data. The PMU controls the temperature-, voltage- and current sensors, to find out if something malfunctions. Subsystems can be disconnected by the PMU, in case of malfunction, to prevent the batteries from being drained. If the system runs normally the management will log the data (housekeeping data). This data will be sent to earth on request. The PMU is a PIC18LF452 microcontroller which has been on the market for some time and is considered reliable by the manufacturer.

The solar cells are connected 5 in a series and placed on 5 sides of the satellite (one cell measures 80*14 mm) which gives an output voltage of approximately 3.0V. The solar cells are monocrystalline single junction cells with an efficiency of 18%.

The battery on board is two single cell Li-ion batteries in parallel which gives 3000 mAh/3.7V.

The report also includes considerations on EMC, reliability and redundancy. Some sensitivity analyses of the DC/DC converters. To be able to test the system a simulator is created. The simulations are made in simulink/dSpace. This simulator simulates the solar cells when the satellite is in orbit. To make this as realistic as possible the simulator switches the subsystems on/off like it will be done in space.

5 Introduction

5.1 The nCube project

The nCube student satellite project is designed and managed by Andøya Rocket Range (ARS) and Norwegian Space Center.

The nCube student satellite project aims to design, build, integrate, test and launch a small satellite. This will give the students "hands-on" experience with a real satellite, multidisciplinary collaboration and space mission experience.
The project has also an intention of building a better bond between the educational facilities in Norway to be able to raise the quality. The participants in the project are Master of Science students from: Narvik University College (HIN), Norwegian University of science and technology (NTNU), University of Oslo (UIO) and Agriculture University of Norwegian (NLH)

One other aspect of the student satellite project is to raise the interest for science and technology studies among high school students in Norway.

5.2 Specifications

Size:	10x10x10 cm
Mass:	1 kg
Orbit:	Low polar orbit (700 km)
Launch site:	Dnepr
Launch date:	Summer 2004

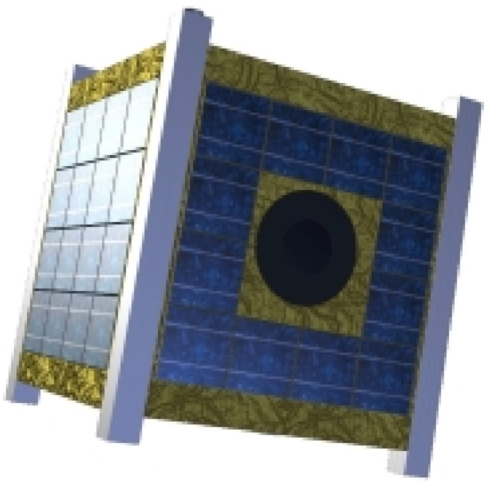

Figure 1: Picture of a cube satellite

5.3 Concept

The CubeSat concept is developed by Stanford University (USA). The concept is developed to be able to launce several satellites at nearly the same time from a launcher. The launcher or the P-POD (Poly Picosatellite Orbital Deployer) is developed by California Polytechnic State University. Each P-POD contains three CubeSats which will be deployed in a sequence. The rocket (launch vehicle) could contain several P-PODS. This is developed to keep a low cost launce.

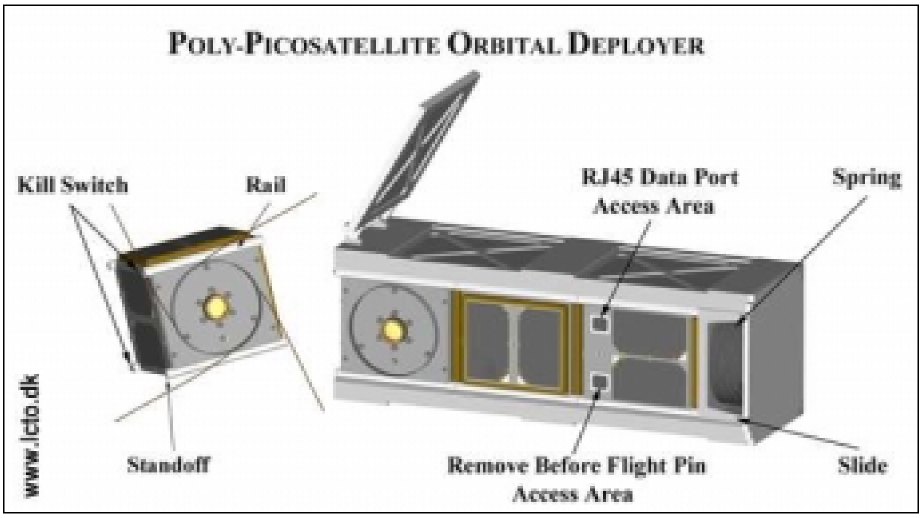

Figure 2: Picture of the P-POD with three cube satellites on board.[15]

5.4 Diploma task

The task is to build a reliable and high efficient power system; supplying all the different subsystems on board the satellite. This includes choosing type of power system, solar cells and battery. The power management system (or the power management unit) should collect, check and log the house keeping data on board the satellite.

The power supply circuit board should also act as a mother board, where all the other subsystems will be attached. This part of the power supply will be referred to as the backplane. The backplane should contain all the traces and connectors distributing power and data in the satellite.

To fulfil the demands of the Master of Science diploma at Narvik University college, three "special topics" are added. Theses topics are:

- Power management – Structure with focus on reliability.
  Limitations: This is theoretical task where the results are considered in the development process.
- DC/DC power converter/ power valve – structure, sensitivity analysis, evaluation of EMC.
  Limitations: This is part theoretically part practically task. The EMC study is generally theory. The sensitivity analysis is preformed in pSpice.
- "Hardware in the loop" – preparation for simulation/ testing in realistic environments.

Limitation: This is a practical task. The simulations are preformed in simulink and dSpace. This simulation shall be done for testing the power condition in a worst case orbit. The simulation shall only test the power system and not the power management system.

5.4.1 Problem formulation

The largest problem when constructing the power supply system is the extreme environment it shall be designed to cope with. There are difficulties with testing the system in a space like environment on earth. Another problem is the small size of the satellite. The size is limiting the available area for solar panels which could make it hard to collect enough energy to support the satellite.

Challenges when developing the satellite:
Size ~80*80 mm
Space environment
- Vacuum
- Temperature

5.4.2 Limitations

Except of the physical demands there is some restrictions regarding the use of the Power management unit (PMU). Due to the small size of the satellite there might be limitations in use of backup solutions to the power supply system. There could be trade-off between efficiency and reliability because of the small size.

6 Satellite construction - Theoretic Part

6.1 Introduction dc-dc converters

[9]

Dc-dc converters are widely used in power supply applications. Their ability to convert and stabilize dc voltage is very useful. Dc-dc converters are often used together with rectifiers to convert ac voltage to a regulated dc. The dc-dc converter is used to stabilize the unregulated dc voltage, which can fluctuate. There are two different unregulated dc voltages in the satellite; after the solar cells and the battery voltage. A dc-dc converter is used for stabilize the voltage in both cases. There are two basic converter topologies; the step-up (boost) and the step-down (buck). By combining them a number of different converters can be built.

All converters use some kind of switching for obtaining a desired output which is independent of the input. This means that the output of the switching is a pulse width modulated signal where the average voltage is the desired one. There is always need for a capacitance to smooth the voltage after the switching.

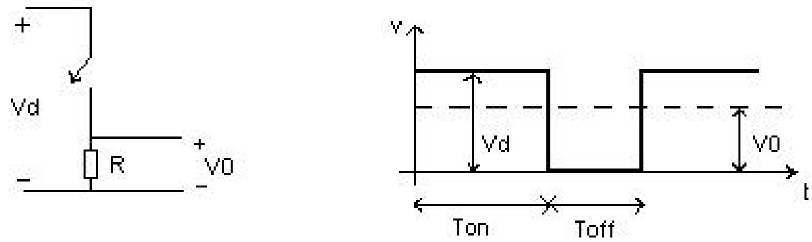

Figure 3: Simple step down converter.

To be able stabilize the output a control system is used. A reference voltage is compared with the actual output. If there is a mismatch, the control system adjusts the duty cycle in the switching. This is made by an OP amplifier and a comparator. The OP detects the error in output voltage and compares it with a saw tooth voltage. This will result in a switch control signal that adjusts the duty cycle if the input voltage changes.

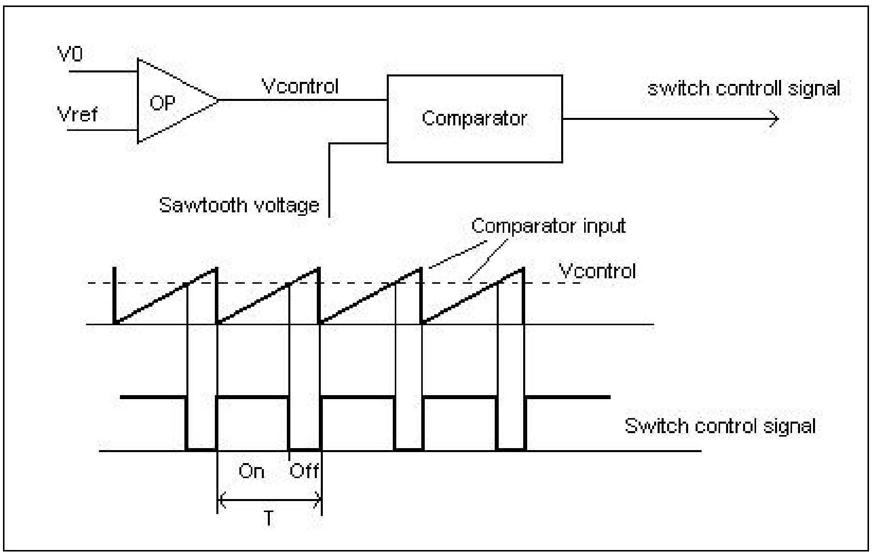

Figure 4: Control circuit used for stabilizing the output voltage.

The switching frequency is often chosen in the range from a few kilohertz to some hundred kilohertz. This makes it possible to stay out of frequencies which could disturb other systems. With a good design and some low pass filtering the problem should be solved.

6.1.1 Step-down (Buck) converter

Step-down converters convert a high input voltage to a lower output one. The ratio t_{on}/T determines the level of step down.

$V_0=t_{on}/T*V_d$

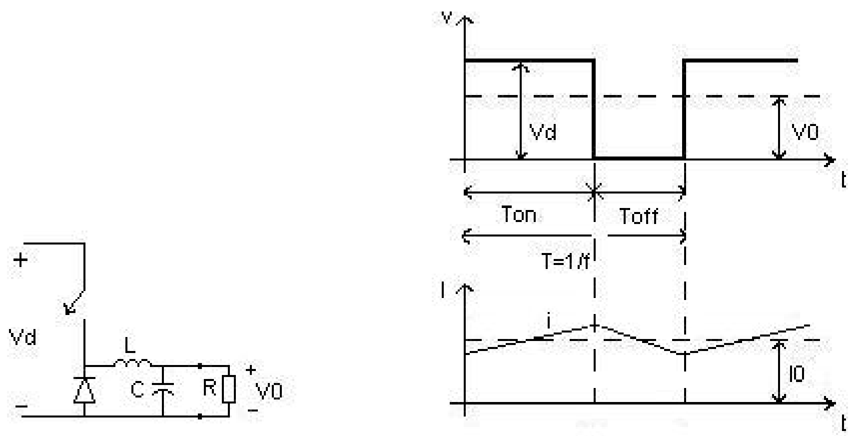

Figure 5: Step down converter. Vd=input voltage. V0=output voltage. i=output current.

It is worth noting that the output voltage is linearly depending of the time t_{on}. This makes it very easy to obtain a desired voltage. The low pass filter is used for different reasons. The switch produces high frequency ripple which the filter short-circuits. It is important to choose the corner frequency of the filter much lower then the switching frequency.
Most applications don't accept that the voltage is zero at the time t_{off}. For this reason the low pass filter smoothes the voltage. The capacitance tries to stabilize the voltage and the inductance is trying to maintain a certain current. If the load isn't purely resistant (this is almost impossible to have) a free-wheel diode is needed. It is anyway needed when a low pass filter is used. The diode conducts the current, that is charged in all inductances, at the time t_{off}.. The inductance in the low pass filter is limiting the efficiency due to the resistance in the coils. The efficiency is usually quite good, ~90%.

6.1.2 Step-up (Boost) converter

Together with the step down converter the step up constitute the basics of converter topologies. The step up converter has a higher output voltage than the input one. The converter is used in power supply applications and when breaking dc motors. As in the step down converter the step up uses switching to obtain a higher output voltage. The main difference between the topologies is that a diode is used, which is reversed biased when the switch is on, isolating the output from the input. At this time the input supplies energy to the inductance. When the switch is of the energy stored in the inductance starts to conduct, together with the input, pushing the output voltage to a higher level. The output capacitance tries to maintain a constant output voltage. Since the voltage of the inductance over a time period T must be zero;

$V_d*t_{on}+(V_d-V_0)*t_{off}=0$

➔ $V_0 = T/ t_{off}*V_d$

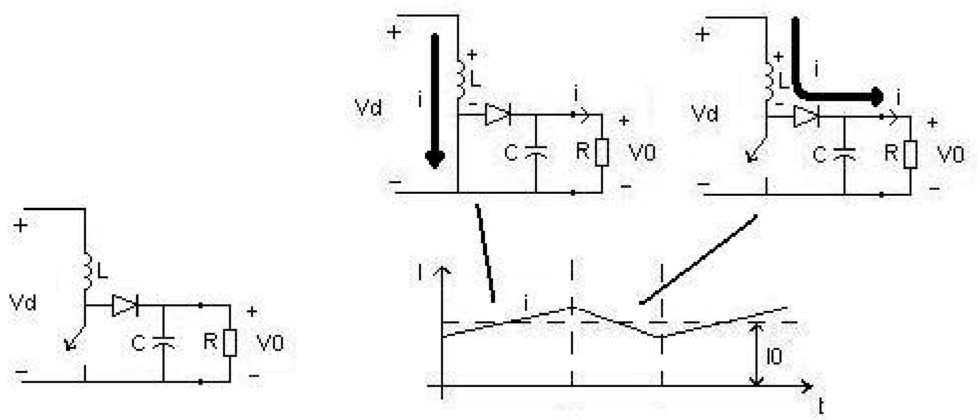

Figure 6: Step up converter. The inductance boosts up the voltage when the switch turns off.

The output voltage is linearly depending on the time t_{off} making it easy to obtain the desired output. As with the step down converter the output ripple will be the same and multiples of the switching frequency. The output capacitance is chosen to stabilize the voltage but there might be necessary to use a smaller capacitance in parallel to reduce the high frequency noise. This is very important if the converter is used in applications that are sensitive to high frequency noise. The efficiency of step up converters is generally lower than the step down. Usually ~85%, ~90% with the step down.

6.1.3 Buck-Boost converter

The buck-boost converter or step-up step-down converter can maintain a desired output no matter which level the input has. The output can be either higher or lower than the input. The converter is the only choice if the input voltage is fluctuating much and a regulated output is needed. Another case is if a varying output voltage is needed. The converter is obtained by cascading the two basic topologies, step up and step down. The two converters combined will result in the single buck boost converter. The output is depending on the input as combining the two converters.

$V_0/V_d=D/(1-D)$ where D is the duty ratio t_{on}/T

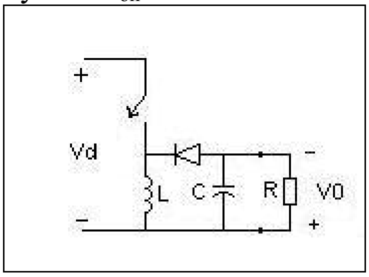

Figure 7: Buck boost converter.

The duty ratio will determine the output voltage which can be set to either higher or lower than the input. When the switch is closed the diode is reverse biased and the inductance will be charged. When the switch opens the energy in the inductance is transferred to the output. The voltage will be equal at the input and output when the duty cycle D is 50%. The voltage has a negative polarity, meaning that the converter inverts the voltage on the output. The diode as well as the resistance in the coils of the inductance will make the efficiency a little poorer. This makes the efficiency of buck boost converters to about 80%.

6.1.4 Cúk converter

The cúk converter is like the buck-boost converter able to both increase and decrease the output compared to the input. The output has a negative polarity in respect to the input. A capacitance C_1 is used for transferring energy between the input and output. The two inductances push current true the diode when the switch is of. The capacitor C_1 is charged by energy from L_1 and the input. L_2 feeds the output. When the switch is on the diode is reverse biased. C_1 discharges true the switch, transferring energy to L_2 and the output.

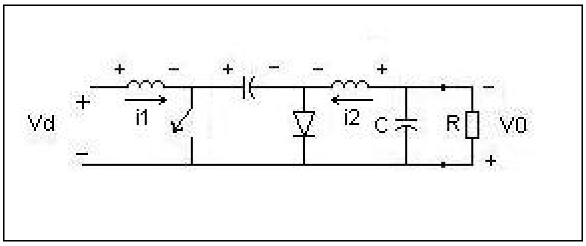

Figure 8: Cúk converter.

$V_0=D/(1-D)*V_d$ where D is the duty ratio t_{on}/T

The big advantage with the cúk converter is that the input and output currents are almost ripple free. The switching frequency has less effect on other circuits with this design compared to ex. the buck-boost. This is because of the nearly constant current transferred true the circuit. This makes it unnecessary to use external filtering.

6.1.5 Full bridge converter

The full bridge converter will only be briefly described. This converter is the only one capable of transferring voltage and current in both directions. Typical applications are dc motor drives and dc-ac conversions. This converter consists of four switches and four diodes. The control of this converter is more complicated than of the previous ones. But the possibilities are big.

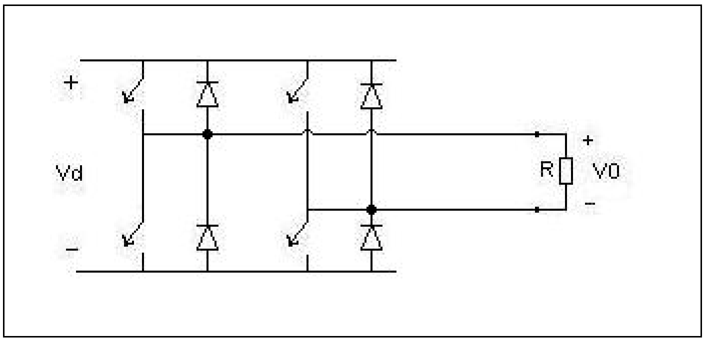

Figure 9: Full bridge converter.

6.2 Introduction to sensitivity analysis

[10]

Sensitivity analyses are made to evaluate how stable the circuits are. Every component has a certain range of in which the labeled component value is in. This is the components tolerance, and it's specified by the manufacturer. A component with a narrow tolerance is more expensive then one with a big range. The sensitivity analysis performs a test which tells if there is any part of the circuit where it's important to use components with good tolerance. The test makes several iterations and finds the biggest diverge from the nominal value of f ex the output voltage. Every iteration has a new set of values within the tolerance. A program called *PSpice* is used for doing the analysis.
There are two tests made to evaluate the circuit; Monte Carlo and worst case. The Monte Carlo test makes a certain number of iterations (set in the program). The values of the components are randomly set by the computer and in the result, the differ from the nominal output is given for every iteration. The worst case test will result only in one value, the state when the output differs most from the nominal value. The worst case test will also tell which component that affects the output most. These two tests will give a picture of how stable the circuit is. If the output varies more then acceptable, better components will be needed.

6.2.1 Buck converter

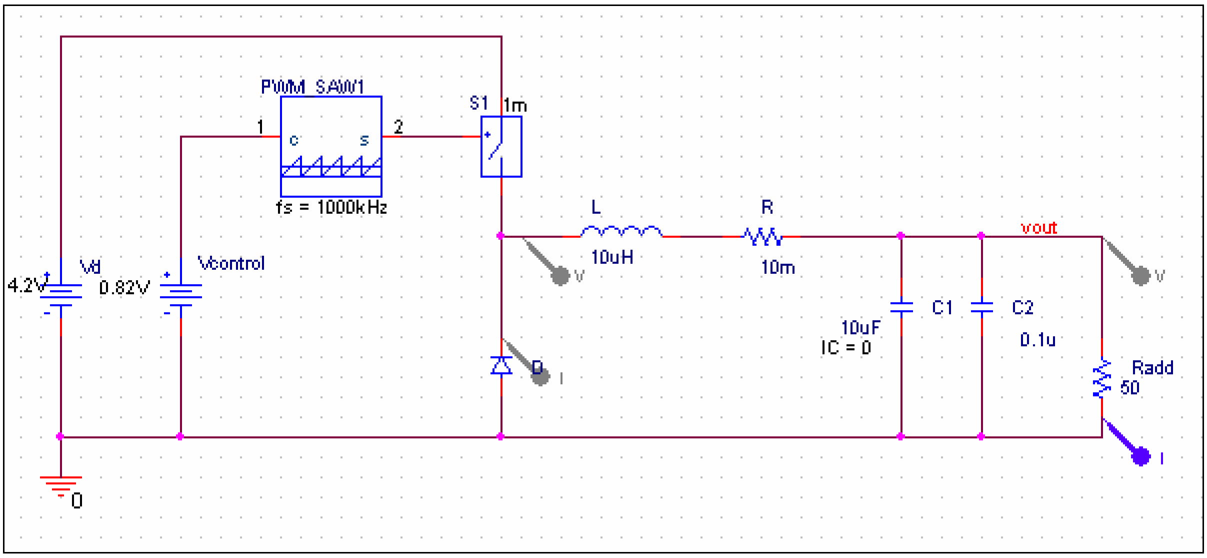

Figure 10: Buck converter used in PSpise simulation.

[14]

Figure 11: Top picture shows the currents, output is top line and thru the diode is bottom line. Bottom picture shows the voltages, output is straight line and input after the switch is the other line.

The circuit is a typical buck converter. The values are set to be as equal as possible as the TPS62203 converter. The output is 3.5V and the load current is about 70mA. The tolerances of the components that are used in the real circuits are 10%. The simulations are made with 10% tolerance as well.

Complete test results is in the enclosures.

6.2.1.1 Monte Carlo analysis:

20 iterations where made.

- *NOMINAL 3.4812 at T = 555.8600E-06*
- *Pass 11 3.582 at T = 532.8600E-06*
  (102.9 % of Nominal)
- *Pass 8 3.4065 at T = 544.8600E-06*
  (97.855% of Nominal)

Monte Carlo test shows that the maximum differ of the output voltage from the nominal value are about 3%.

6.2.1.2 Worst case analysis:

The worst case according to the test occurs when all components are set as high as possible.

- *NOMINAL 3.4812 at T = 555.8600E-06*

- *ALL DEVICES 3.5337 at T = 501.8600E-06*
  (101.51% of Nominal)

The worst case analysis shows that the maximum differ from nominal output voltage is about 1.5%.

The component C2 is the one that affects the output value most.

C_C2 C_C2 C 3.545 at T = 545.8600E-06
(18.341% change per 1% change in Model Parameter)

6.2.2 Boost converter

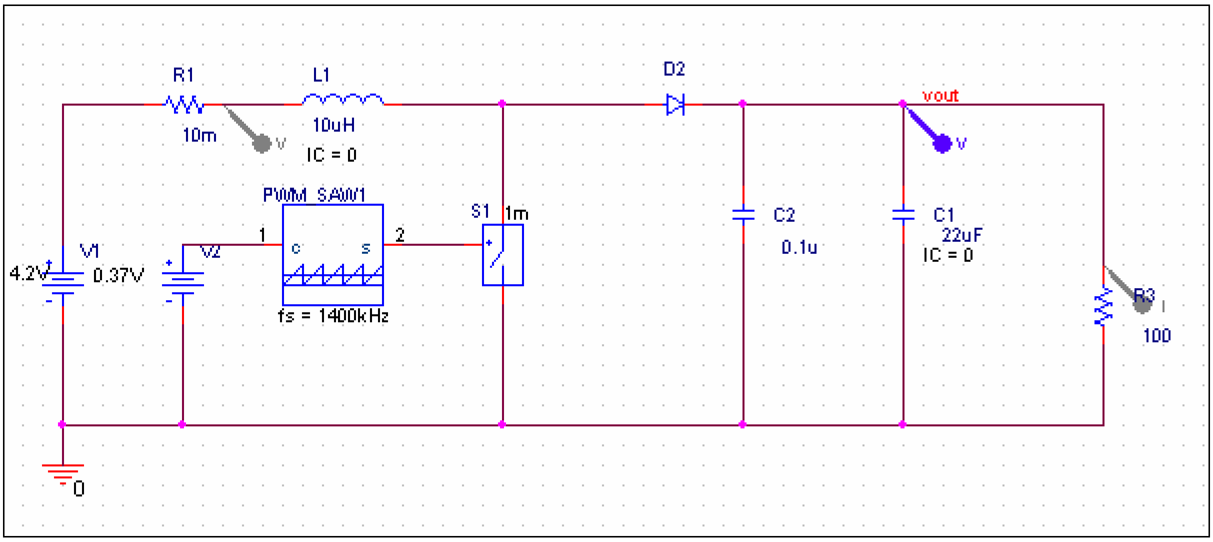

Figure 12: Boost converter used in the PSpice simulation.

[14]

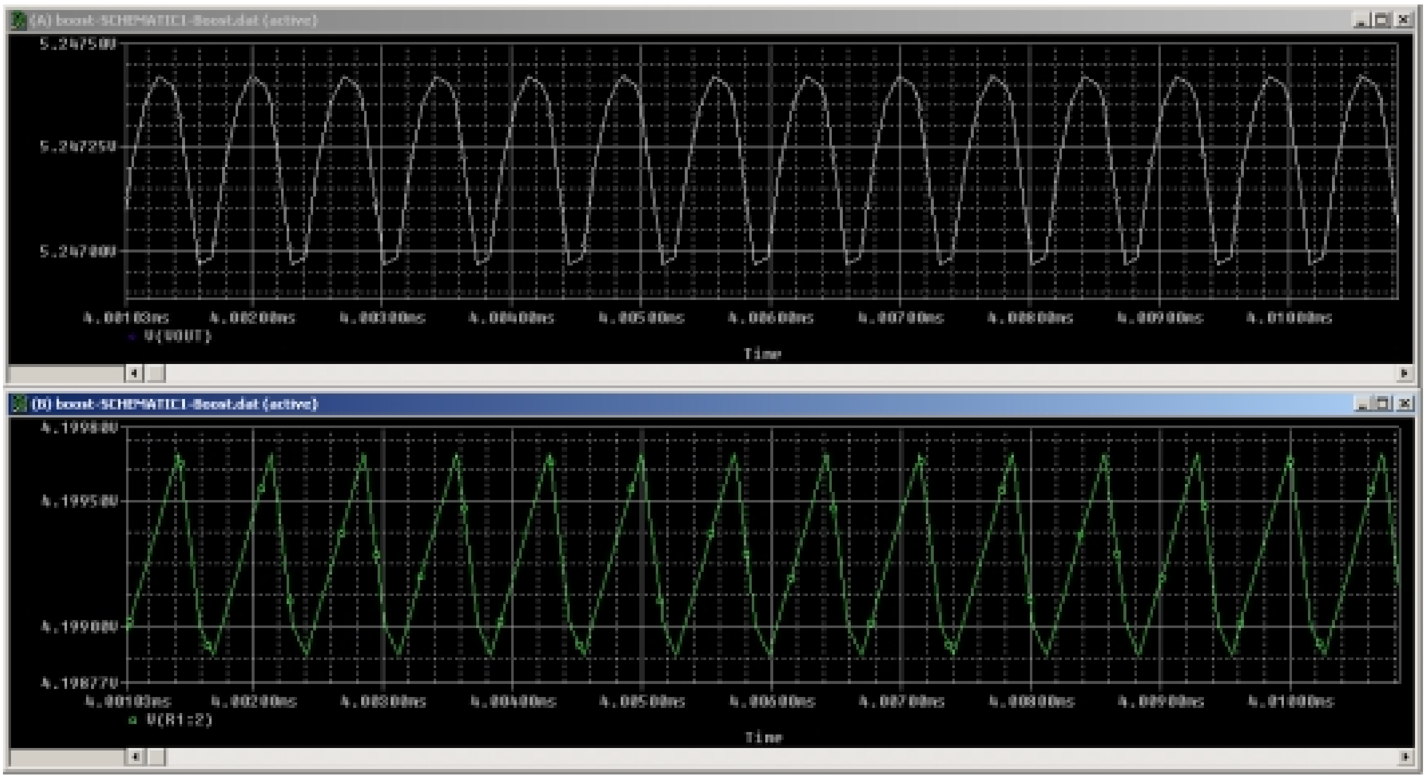

Figure 13: Voltages in the boost converter. Input in bottom and output on top.

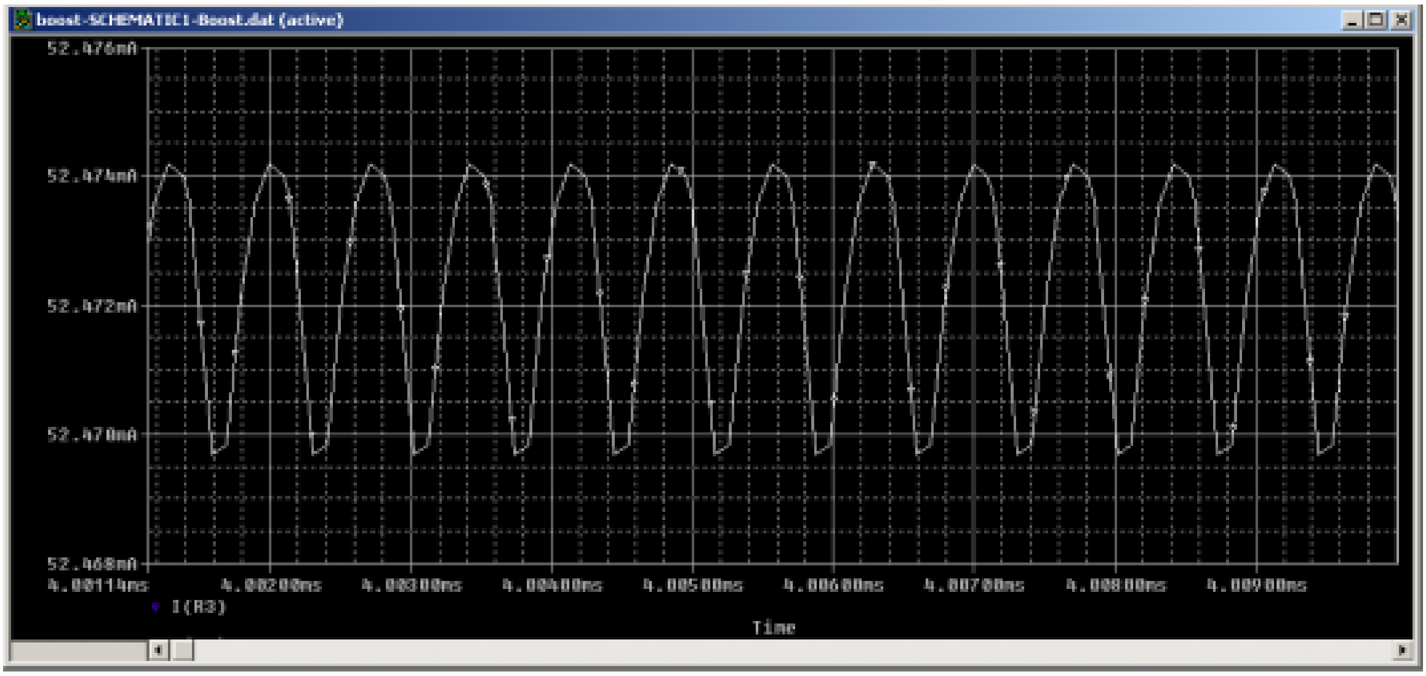

Figure 14: Output current of the buck converter.

This is a typical boost converter circuit. The values are set to simulate the MAX1896 circuit used in the satellite. The tolerance is 10% on all components. The output voltage is tested and the nominal value is 5.25V. The load current is 52mA.

Complete test results is in the enclosures.

6.2.2.1 Monte Carlo analysis:

20 iterations where made.

- *NOMINAL 5.2474 at T = 4.0006E-03*
- *Pass 17 5.3119 at T = 4.2798E-03*
  (101.23% of Nominal)
- *Pass 4 5.2446 at T = 4.0006E-03*
  (99.947% of Nominal)

Test shows that the maximum differ of the output voltage from nominal value are about 1.2%.

6.2.2.2 Worst case analysis:

The worst case according to the test occurs when C1 and L1 is decreased R3 is increased and C2 is left unchanged.

- *ALL DEVICES 5.5708 at T = 4.0034E-03*
  (106.16% of Nominal)
- *NOMINAL 5.2474 at T = 4.0006E-03*

The Worst case test shows that the maximum differ of output voltage from nominal value is about 6%.

Component R3 affects the output most.

R_R3 R_R3 R 5.2475 at T = 4.0006E-03
(5.8157E-03% change per 1% change in Model Parameter)

6.3 Solar cells

[17]

A solar cell is a kind of semiconductor device that takes advantage of the photovoltaic effect, in which electricity is produced when semiconductor's PN junction is irradiated. When light strikes a solar cell, one part of it is reflected, one part of it is absorbed and one part of it passes through the cell. Photons from the absorbed light excite the bound electrons into a higher energy state, making them free electrons. These free electrons move in all directions within the crystal, leaving holes where the electrons used to be. These holes also shift around in the crystal. The electrons (-) collects in the N-layer, the holes (+) in the P-layer. When the outside circuit is closed, the electricity flows.

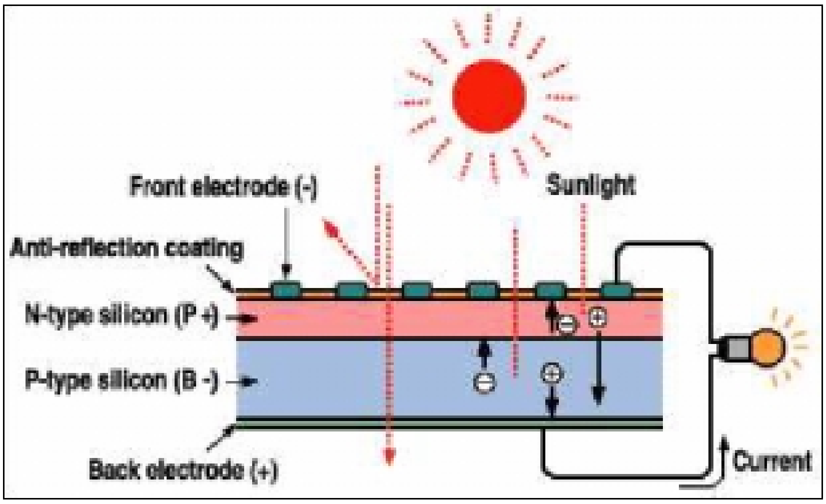

Figure 15: How a solar cell works.

6.3.1 Calculations

The efficiency (η) is given by the formula:

$\eta = \frac{J_{sc} V_{oc} FF}{\frac{P_{in}}{A}}$, J_{sc} = short circuit density, P_{in} = Optical input power, V_{oc} = open circuit voltage, FF = Fill Factor, A = area

The optical power input depends on which wave length the solar cells uses to excite the electrons in the material into a higher energy state. The Fill Factor is explicit to the type of crystal used.

The Fill Factor (FF) is given by the formula:

FF = $\frac{V_{mp} J_{mp}}{J_{sc} V_{oc}}$, V_{mp} = maximum power voltage, J_{mp} = maximum power current

Theses values could be determined by a maximum power tracker.

6.3.2 History

Practical solar cells have only been available since the mid 1950's, but the phenomenon was discovered by a French scientist Henri Bequerel in 1839. The firs solar cell used in space was supplying a radio on board "U.S. Vanguard I" in 1958. Since then the solar cells have been used in most spacecrafts. The solar cell technology has been developed much since then.

The first solar cells where P/N cells (positive doped layer on top) made of silicon (Si) produced by Bell Laboratories. These cells had an efficiency of 7-8%. In the late 1950s, after Van Allen identified the radiation belts around the Earth, ground tests where made to determine the degradation rate of silicone cells. The test showed that N/P cells where more radiation resistant then P/N cells. Therefore the industries mainly produced N/P cells.

In the 1960s silicone cells where still the best available, but the efficiency had increased to 12%. Thin film Cadmium Sulfur (CdS) where investigated, but the efficiency was to low, and they where to unstable.

In the 1970s development of terrestrial cells became important and several different crystalline forms of silicone where tested. The terrestrial solar cells marked demanded low cost, which gave solar cells with lower efficiency then the one produced for space applications. The real breakthrough came when significant developments of semiconductor where made, and this led to the firs Gallium Arsenide (GaAs) with efficiency up to 18%. Also Indium Phosphor (InP) where discovered with efficiency up to 18%. These cells where particularly interesting in space use, but behavior wasn't as pronounced. Silicon cells served as the only cell for space use.

The cells described continued to develop in the 1980s. Because of very expensive production the InP cells got shifted to GaAs cells. The GaAs cells showed great efficiency and radiation tolerance. They also had a smaller fall-off in efficiency at higher operating temperature. One thing that where better with the silicon cells where the breakage strength. The technology was used to grow GaAs cells on Germanium (Ge) substans which had a greater mechanical structure. Later Aluminum Gallium Arsenide (AlGaAs) cells and Gallium Indium Phosphor (GaInP) grown over the GaAs cells and multi junction cells where made. Efficient had now reached 21%

In the 1990s the space facilities need more power and the high efficient solar cells where preferred even though the manufacturing costs where 6-9 times higher. To day triple junction solar cells could deliver power whit efficiency up to 30%.

6.4 Batteries

[17]

The batteries store the energy chemically. Batteries are divided into primary and secondary systems. Primary systems usually have a better performance than secondary systems, but the primary systems are not rechargeable. Therefore they are of no interest in space applications.

Specific energy [Wh/kg] and energy density [Wh/L] is often referred to at energy density. Here some considerations regarding rechargeable batteries. Li- batteries are lighter and smaller then the other and therefore the energy density are much higher. But there are some problems with safety regarding these batteries. The Li- metal are not fully developed and never been used in space applications. Li-Ion batteries have been on the market for some time and have good energy density, not as high as Li-metal but instead they are much more stabile.

Nickel Cadmium (Ni-Cd)

Advantages

+ Log cycle life
+ Rugged; can withstand electrical and physical abuse
+ Reliable; no sudden death
+ Good charge retention
+ Excellent long time storage
+ Low maintenance

Disadvantages

- Low energy density
- Higher cost then lead-acid batteries
- Contain cadmium, which is toxic
- Memory effect

Nickel-Metal Cadmium Hydride (Ni-MH)

Advantages

+ Higher capacity than nickel cadmium
+ Sealed construction, No maintenance
+ Log cycle life
+ Cadmium-free; minimal environmental problems
+ Rapid recharge capability
+ Long Self life in any state of charge
+ High voltage

Disadvantages

- Higher rate performance not as good as with Ni-Cd
- Higher cost then Ni-Cd
- High charge retention
- Moderate memory effect

Nickel Hydrogen Batteries (Ni-H_2)

Advantages

+ High specific energy [Wh/kg]
+ Long cycle life
+ Long life time in orbit
+ Tolerates overcharge and reversal
+ H_2 pressure gives an indication of state of charge

Disadvantages

- High initial costs
- Self discharge proportional to H_2 pressure.
- Low energy density

Rechargeable Li- metal batteries

Advantages

+ High specific energy and energy density
+ High voltage
+ Good charge retention, low discharge rate

Disadvantages

- Low life cycle
- Relatively poor high rate performance
- Relatively poor Low temperature performance
- Capacity fading
- Potential safety problems

Lithium Ion batteries (Li-Ion)

Advantages:

+ Sealed cells; no maintenance required.
+ Long cycle life.
+ Broad temperature range of operation.
+ Long shelf life.
+ Low self-discharge rate.
+ Rapid charge capability
+ High columbic and energy efficiency.
+ High energy density and specific energy.
+ No memory effect.

Disadvantages:

- Moderate initial cost.
- Degrades at high temperatures.
- Need for protective circuitry.
- Capacity loss or thermal runaway when overcharged.
- Venting or possible runaway when crushed.

By study these different types of batteries the choice fell on Li-Ion batteries because they have high energy density and seems to have a long life time.

Problems with Li-Ion batteries are that they are vulnerable and very sensitive to over discharging and charging. Normally a protection circuit is attached to these batteries directly from the manufactures. This circuit disconnects the battery if the voltage drops below 2.3 volt and closes again when the voltage increases to 3.0 volt. The same thing happens when overcharging the battery; it opens at 4.3 Volt and closes again at 4.0 volt. This circuit also protects against short-circuits. The batteries for the satellite there is no such circuit so all this must be done by the power system itself.

Charging Lithium Ion batteries
When charging a Li-Ion battery both the charging current and voltage must be regulated. The charging is divided in to two steps

1. Charging with constant current.
2. Charging with constant voltage

When charging with constant current, the current must be limited to the manufactories specified maximum charging current, normally 0,7 CmA, (0,7 * specified mA/h)
This is done until the battery voltage rises to the maximum voltage, specified by the manufactories, normally 4.1 – 4.2 Volt.
Then the constant voltage charging is taking over. By charging the battery with a constant voltage until the charging current drops down to a specified value (normally 0,05CmA), the battery is fully charged.

6.5 Reliability

6.5.1 Reliability definitions

[1]

Reliability in context of space mission; a common definition is:

> *"The probability that a device will function without failure (of any kind) over a specific time period or amount of usage"*

The mission reliability which is more important is defined:

> *"The probability that a device will function without failure (that impairs the mission) over a specific time period or amount of usage"*

When reliability is discussed; it means mission reliability. When you're speaking of mission reliability is important to determine the mission "success criteria". "Success criteria" means what should be the minimum requirement to call the mission a success.

The “success criteria” for the nCube satellite is to get a launch and to be able to listen to it at least one time. This means that if the ground station is able to track the satellite in orbit the mission is a success. The total life time for the satellite will varying from 2 to 6 months depending on height of the orbit.

6.5.2 Typical steps for achieving a reliable system

[1]

1. *Keep it simple. Every additional function or component increases the failure probability*

When designing the power supply; simplicity has always been in mind. There is always a trade of between simplicity/reliability and reliability in more complex architecture. The power supply has been based on DC/DC converters which is a good way to handle different voltage levels and to turn on/off subsystems. But each DC/DC converter is an introduction to a poorer reliability. The number of DC/DC converters has been limited by using as few voltage levels as possible. This makes it possible to couple different systems on a single converter. This makes the system weak because if a single converter fails; more than one system will influenced. This could be solved by some kind of redundancy. The best way to provide power is to hard-wire the most essential systems. To be able to hard-wire systems, they must cope with an un-regulated/battery source which will vary from 3.3V to 4.2V. With the systems hard-wired; the possibility of switching them on/off will be excluded. An example on the trade-off problem (simplicity/reliability and reliability in more complex architecture); the power management is controlled by a microcontroller. The microcontroller continuously runs through a program controlling temp, current and voltage sensors. It is also checking and logging the values and is allowed to turn on/of systems if problems occur. This is positive if a problem is detected and the problem gets eliminated. But again a microcontroller and its program are decreasing the reliability, because it’s a new source to create failures.

2. *Assure adequate strength (mechanical an electrical) of all parts. Including allowance for unusual loads due to failure in related components.*

All the components that are chosen on the satellite should cope with the double of which is demanded (if possible). Teflon wires are used because they are more reliable considering high temperature and vacuum.

3. *Provide alternatively means of accomplishing the most essential functions where design for excess strength is not suitable.*

Except hard wired systems; some systems like gravity boom and antennas are released by a timer that is trigged by the kill switch. This means that even if the satellite is “dead” the antennas will be released and be able to send some kind of ID to be recognized. This alone will make the mission a success.

4. *Plan a test program to assure that the above objectives have been achieved.*

This is very important; if there is some kind of plan it will lure out many unnecessary failures early in the process. The power system has been tested part by part before connecting them together to a complete power management system. The system integration (the whole satellite) should also be followed by complete test of communication off and on board the satellite. Before launch a vacuum, tumble and temperature test will be completed.

Since the satellite isn't finished by the end of this report, the only system test (on the complete power management system) that is made; is by use of the simulator created in this project. This is discussed in chapter "Simulations with dSpace".

5. *Collect and analyze of tests and on-orbit failure data to guide further design and mission plans*.

This report will be a collection of all the tests, test-results, pit falls, improvements and even thoughts that have occurred during this project.

6.5.3 Introduction to reliability calculations

The Power management system is definitely the most essential system on the satellite. This system includes: distributed power system (DPS); DC/DC converters that feeds the subsystems. The backplane; where all the connectors hence all the power/communication traces and all the current/ voltage sensors are placed. Power management unit (PMU) which controls and log all the house keeping data, and in the end the solar cells and the batteries which is the only energy source on the satellite. Therefore is it adequate that it is designed with reliability in mind.

The next pages in this report contain information on how reliability is calculated. There are some considerations on how PCB should be designed; it also contains information on how to build the distributed power system with a microcontroller that handles the management. There are also some thoughts on solar cells and batteries.

6.5.4 Reliability calculations

[4]

Reliability calculations are often measured in mean time between failures (MTBF). Typical for military and space use is 400 000 hours at 50 degree Celsius.
MTBF = mean time between failures
MTTR = repair time
MTTF = mean time to failure
FIT = failure in time
λ = failure rate
Mathematical MTBF is described as:
MTBF = (MTTF + MTTR) = MTBF = MTTF = $1/\lambda$. (Repair time is often neglected.).

The inverse of MTBF is the failure rate (λ). The failure rate is defined as the relation between the number of failure and the using time for the given quantity of components.

The reliability function is then given by $R(t) = e^{-\lambda * t}$ (success probability). And hence the failure probability F is given by F= 1-R. R (t) is the probability for a component/system functioning without failure for a given time t. Mean value of R(t) is given at t=$1/\lambda$ which is mean time until a failure occur (fig b).

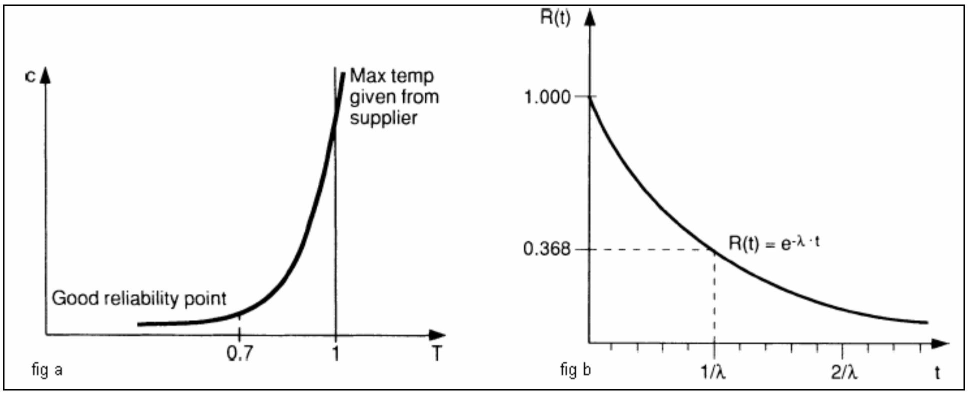

Figure 16: Fig a shows how the acceleration factor depends on temperature. Figure b shows the mean value of R(t) given at t = 1/λ which is the mean time until a failure occur.

An example is for a given part; MTBF = 100 years (given by a data sheet). Then the probability for the system not to fail with in 5 years is given by $R(5) = e^{-\frac{5}{100}} = 0{,}95$. Accordingly the probability for the system not to fail in the first 5 years is 95%

Predicted value; is a calculated value using ground environment failure rates and accelerator factor. Accelerator factor C is mainly depending on temperature (fig b). Therefore the failure rate should be multiplied by the acceleration factor $\lambda = C * \lambda_b$. Estimated value or proven reliability; is the ratio between accumulated component hours and observed failures. Predicted value and estimated value are often more or less the same, but estimated value is more realistic when the application is used in the same environment as the data is collected from. This environment is often room temperature, normalized voltage and load. A "rule-of-thumb" when calculating reliability is to use 0.7 of the maximum value described in the data sheets, and then a good reliability can be expected.

6.5.4.1 An example on how to calculate the DC/DC converters reliability (FIT)

[2]

Maxim are calculating there acceleration factor with an equation giving the enhancement of temperature on the failure rate at two temperatures.

The equation: $C = e^{[(\frac{E_a}{k_b})*\{(\frac{1}{T_u})-(\frac{1}{T_s})\}]}$ where C is the acceleration factor. This formula could be used to find the acceleration factor between any two temperatures, if the activation enegy is known.

$E_a = k_b * \ln[C]/\{(\frac{1}{T_u}) - (\frac{1}{T_s})\}$ the activation energy in [eV],

k_b = Bolzmann constant, $8.617*10^{-5} \left[\frac{eV}{K}\right]$

T_u = use temperature in [K]

T_s = Stress test temperature in [K]

To find E_a it is possible to use existing activation energy information which is between 0.7 [eV] and 1.2 [eV]. Or you have to measure it. When measuring the activation energy two different groups of components in two different temperatures are used.

Component 1: 60/1000 failures in 100 hours of operating in 150°C, 423°K
Component 2: 15/1000 failures in 100 hours of operating in 125°C, 398°K
The acceleration factor between the two groups are given

$$C = \frac{60}{1000} * \frac{1000}{15} = 4$$

The activation energy is given by

$$E_a = k_b * \ln[C]/\{(\frac{1}{T_u}) - (\frac{1}{T_s})\} = 0.8 \text{ [eV]}.$$

If a given test of 100 components is tested in 1000 hours, the component type is tested for 100000 components hours, if there was 2 failures in this selection the MTBF= 100000/2= 50000 hours. The failure rate $\lambda = \frac{1}{MTBF} = \frac{1}{50000} = 0{,}00002$

R-function would be $R(1000) = e^{-\frac{1}{50000}} * 1000 = 0{,}98$ which means that the possibility of the component not to fail in 1000 hours is 98%. Usually Failure rates are usually described in FIT because they are so small. FIT is the number of failure per billion component hour. λ In FIT = 0.00002/10^{-9} = 20000 FITs.

6.5.5 DC/DC converters

[3]

There are three factors that are deciding the reliability on a DC/DC converter.

1. Number of components it contains
2. The level of stress placed on those components
3. The device's ease of assembly

6.5.6 The DC/DC converter used on the nCube satellite

There are three different DC/DC converters on board the nCube satellite. These are chosen from a large assortment of converter that has been tested. There have been several layouts using different capacitors and inductors. This assortment was chosen with three things in mind.

1. That it was capable of handling the demands on voltage and currents with a good margin.
2. The number of components surrounding the DC/DC converter should be minimized because of reliability. Also try to keep the packages as small as possible
3. The DC/DC converter should have true-shut down.

After the selection was made they have been tested properly. The Ripple has been minimized, the spectrum has been analyzed and the efficiency has been tested with different load (documented in the practical part of this report).

Type	Output voltage	Max load current	MTBF (H)	FIT
TPS62203	3.3V	150mA	1,526E+08	6.555*
MAX1524	4.2V	1500mA	1,348E+08	7.417**
MAX1896	5.5V/6.5V	450mA	N.A	N.A

Figur 17: Shows the data on the different DC/DC converters used on the nCube satellite.

*enclosure XX
** [12]

Generally Maxim uses E_a = 0.8 [eV], and a 60 % upper confidence level at 135°C for 1000 hours when calculating the FIT rate. Texas Instruments uses E_a = 0.7 [eV], and a 60 % upper confidence level at 150°C for 500 hours when calculating the FIT rate.

6.5.7 A products lifetime

[4]

A products life time is often described with the bath-tub curve. This curve shows three different stages in a new product life cycle.

Infant mortality (High but decreasingly failure rate)

In this period the weak components are ruled out through different electrical tests, visual inspections and a burn-in test. The burn-in test is a test where the components are put in to operation for a predetermined time in room temperature followed by a 100% ETA-testing. The reason for these failures is because of defects in technology, bonding, mechanics or die-attach. This makes it possible to provide good outgoing products.

Useful life time (Low and constant failure rate)

It's from this period that the number which is used in reliability calculations is collected. No tests or burn-in process can reveal the errors; they are mainly random and caused by temperature or voltage stress.

Ware out failures (Increasing failure rate due to ageing)

The life cycle for the component has ended.

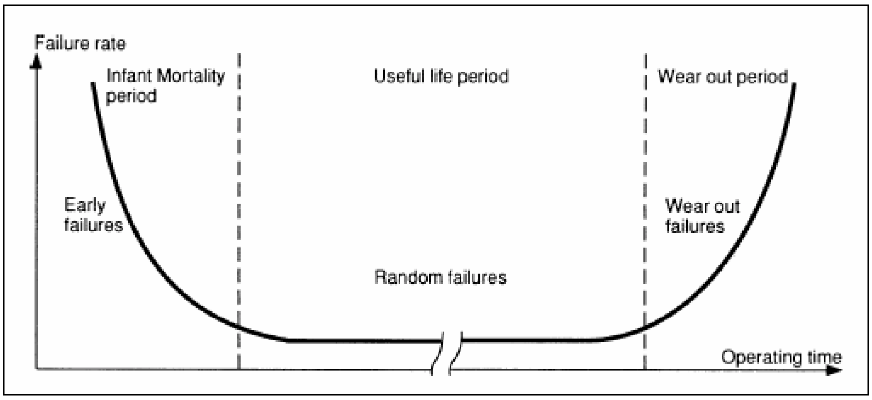

Figure18: Shows the "bath-tub-curve" which shows the three distinct periods in a products life cycle.

6.5.8 Distributed power system (DPS)

[5]

On the nCube satellite a distributed power system is chosen. This of course has benefits and challenges. All the power components will be placed on one place and distributed throughout the whole satellite. The disadvantages with such a system are often long time developing because of the custom design; this again makes the power supply less reliable. Centralized power supply would also introduce problems with heat centralizing, bus impedance, bus resistance and problem concerning the power bus structure. Benefits with DPS is that all the power components are placed together on a shielded board. This makes it easier to control the electromagnetic interference (EMI). The system will also be very efficient because it's custom made.

6.5.9 Introduction DPS structures

[5]

There are several DPS structures. The similarity between them is that they all distribute the power to several power processing units (PPU) which on the nCube is DC/DC converters.

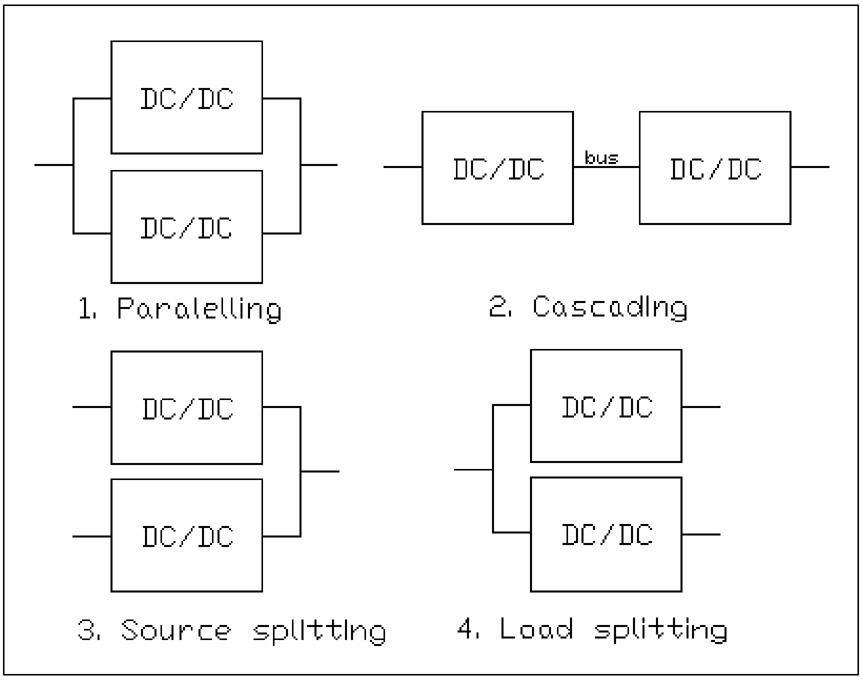

Figure 19: Shows the different distributed power systems architectures.

The first DPS structure is paralleling. This structure is referred to as modular power supply. The advantage with this structure is that each power processing units (PPU) only handle some of the total power. This makes the design easier because the demand and stress on the converter is reduced by the number of PPU used in parallel. The paralleling system could also introduce redundancy; if the system needs n PPU's to handle the load; (n + 1) PPU could be used. The system then has one PPU in hand if one should fail. This is also used in bigger systems and makes it possible to change defect modules when systems are in use (hot swapping), without changing the system ability.

The second DPS structure is cascading. This is necessary in most power system to keep an intermediate bus in the power system. It also makes it easier to handle variations in the input voltage. When using cascade coupling of PPUs; it's possible to put one PPU directly on the logical board; next to the load. The voltage on the intermediate bus could be raised to a higher level to reduce the distribution currents hence the distribution losses in the bus are minimized and the overall system efficiency is increased. When using a higher voltage lever when distributing the power; the distribution harness gets smaller, lighter and less expensive.

The third DPS structure is source splitting. This is when you use more than one power source to supply a common load. This is natural in systems with battery backups; if the primary source gets disconnected a battery package temporarily provides the necessary power. This could also be used to supply power to the equipment in separate utility phases. Redundancy is achieved by using different power processing units (PPU) for each phase. Multiple power distribution buses would with separate PPU also create redundancy.

The last structure is Load splitting. Here different power processing units (PPU) is used to supply different loads. In large systems where the power is distributed over long distances this is a necessity due too conduction loss. It's also required in complex power systems with several voltage stages using separate PPU for each load. When using two converters between any two loads with there filters noise will be eliminated. Load splitting gives the possibility to use selective battery back-up. When using separate converters to different loads; it's possible to back-up only the most crucial part of the system and therefore reduce the battery size.

6.5.10 PCB layout

[6]

Switch mode power supply is a lot more efficient then linear power supplies; but of course there are some drawbacks as well. Because of the switching electromagnetic interference (EMI) is introduced. The EMI spectrum starts at DC/DC switching frequency (on the nCube satellite the DC/DC converters have a switching frequency from 1 to 1.4 MHz) and can exceed over 100 MHz. To be able to reduce the magnetic couplings, parasitic inductance and capacitance the PCB layout has to be studied before the traces and the components could be placed. More about the EMI in the "Electro magnetic considerations" chapter.

The first decision that was made to handle these problems was to isolate the converter. All the DC/DC converters are placed face down in the bottom of the satellite. The Power PCB is part of the Backplane which consists of 2 double layer PCBs with a ground plane which separate the power PCB from the "signal" Backplane PCB.

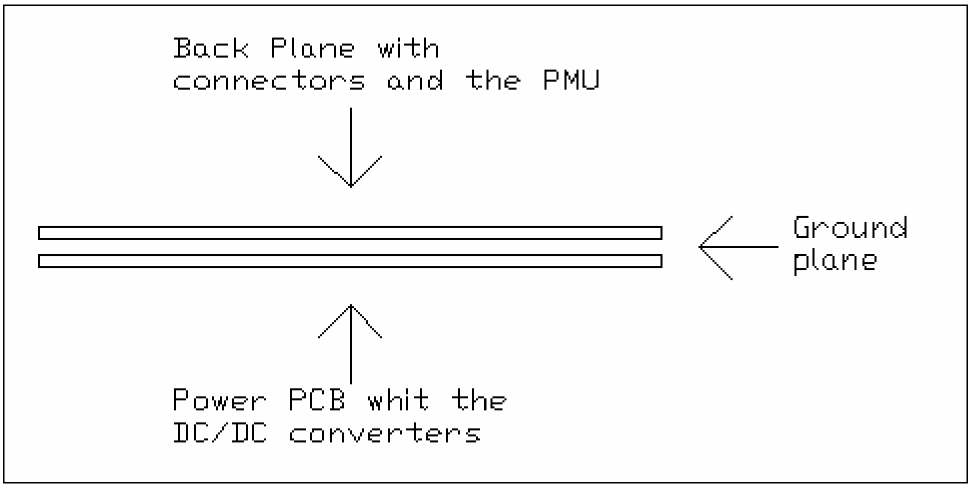

Figure 20: Shows how the Backplane is constructed to separate the DC/DC converters from the rest of the system; using a separate cards and a ground plane between.

Trace resistance is also a factor which is evaluated. Because of limited space on the board some trade off has been made. The limited size (only 80mm) and the small currents; the resistance wouldn't be of such a major problem. But all the traces have been kept as short and slender as possible.

The resistance of the Trace is given by $R = \rho * \frac{1}{s}$ where S is trace area in m^2, and p is the resistively in copper $1{,}7*10^8\,\Omega/m$ (increases with the temperature).

The parasitic inductance is 10nH for 1 cm trace. This implicates short and wide traces. Limit the use of vias, and place the all of the components on the component plane and try to keep the ground plane clean. This will reduce the problem.

6.5.11 Power Management unit

[7] [8]

6.5.11.1 Embedded system:

An embedded system is a stand-alone system. An embedded system handles a small task; or a part of a bigger task continuously. The system runs the same program over and over again (firm ware). Embedded systems are often connected to physical systems. If a system should work as an embedded system there are a few requirements to follow.

1. Throughput
2. Response
3. Reliability
4. Power consumption
5. Cost
6. Physical measurements

Almost every intelligent electrical application now a day has a microcontroller embedded. An embedded system often works in real-time. One example is a car; there are often a couple of dozen small embedded systems working with there tasks like ABS brakes, air-conditioner and fuel level.

6.5.11.2 Real-time-system:

Real-time-system could be but in to two categories; the one with hard and soft response claim. A real-time-system also has to solve its tasks in a logical correct way. If any of these to claims fails; the system has failed.

One example on a hard real-time-system is F-16 fighter. If one system doesn't respond within 1/100 of a second, the fighter will go down. One example of a soft real-time-system is a mobile telephone or a MP3 player.

6.5.11.3 System architecture:

There are several system architectures to use when developing an embedded system. It's important to follow some kinds of rules when developing an embedded system.

Round Robin is only used in "soft" real time systems. The Round Robin architecture starts in the beginning; works through the whole code; then starts again from the beginning in an infinite loop. The response time in this architecture is the time of the entire code.

Round Robin with interrupt works like Round Robin but interrupt is introduced to handle the response. This also gives the programmer control over priority. Worst case response time is the length of the whole main code + the sum of all the other interrupts depending on priority. This architecture is ok to use if there aren't too many interrupts.

A little more complex architecture is Function queue. The interrupt routines put a function pointer in a queue of pointers. The pointers have been ranked with priority. This could introduce the shared data problem and functions could be blocked. The waiting time for the lowest ranked interrupts could be very long. Optimized code is very complex and not very robust.

RTOS (Real-Time-Operating-System). Operating system; that handles the communication between the main task and the interrupts. Is not in use of shared data; and there are no loops that controls the order of the functions. Worst case waiting time is the time the interrupt routine. It's very simple and well arranged to handle. It's pretty expensive and needs a lot of memory; but really an ideal way of developing an embedded system if system is of some size.

Problems concerning embedded systems; is testability and debugging. How to be sure that the code is properly tested in all possible ways. Implementation could also cause some problems depending on architecture and equipment.

The nCube satellite is defiantly an embedded system, when looking at the requirements to complete such a system. The satellite will operate in real-time; it's defiantly a stand alone system with strong demands on reliability. During the developing of the power supply/ power management system; power consumption and physically measurements as well as cost has been of a high level of aspiration

The system architecture chosen is Round Robin with interrupt. This is because the program is pretty simple. It only consists of 6 blocks and two interrupts. This is discussed in the chapter "program code".

6.5.12 Solar cells

There have been made a decision of applying 6 solar cells in series pr side. One single solar cell supplies about 0.5V and a series of 6 cells approximately 3.0V. When connecting a series of 6 cells on each side leads to very small cells. They will measure 14 * 80 mm.

The current delivered from a single cell is determined by the area and the sun density (and of course the efficiency of solar cell).

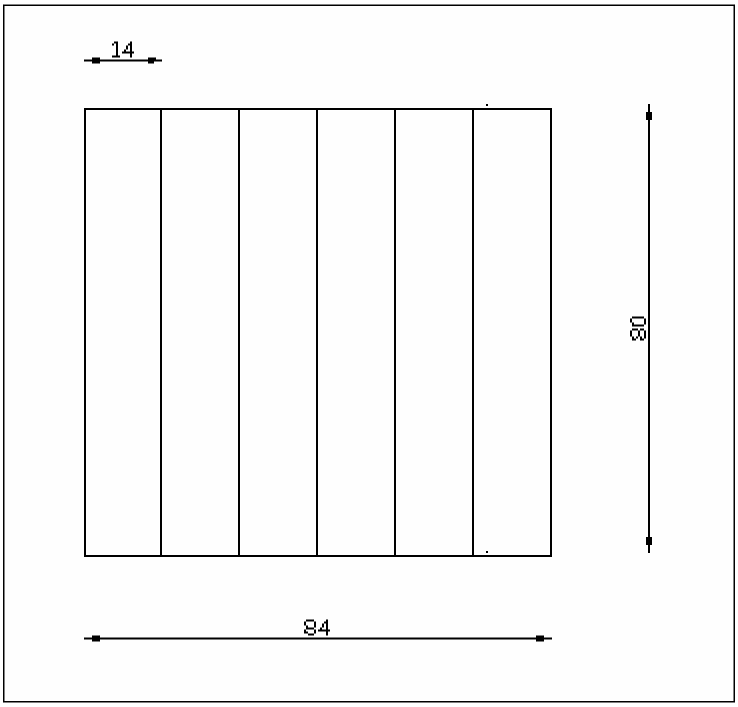

Figure 21: Showing one side of the satellite with 6 solar cells 14*80mm

One problem with many small cells; is that the best cell isn't any better than the poorest in the series. This means; if one cell gets damaged and looses 20% of the area; the other 5 cells also drop with a 20%. Or if 3.33% of the total surface gets destroyed; the power loss will be 20%.The solar cells are very vulnerable and therefore not that reliable. But this decision was made as a tradeoff to be able to charge the batteries which needed 4.2V. Finding a DC/DC converter that could handle currents until 1.5A; the transformed voltage gap should be small therefore 6 cells pr side/ 3.0V output from the solar cells where chosen.

Description	Energy in [W/m2]	Area [m2]	Efficiency	Angle	Power [W]	[V]	[A]
Nadir (45°) + A (45°)	1352	0,006720	18 %	0,7071	1,15639	3	0,3855
Nadir (45°) + A (45°)	1352	0,005376	18 %	0,7071	0,92511	3	0,3084

Figure 22: Shows the power loss of 20%, when only 3.33% of the surface is destroyed.

The voltage falls when the temperature raise. This is a problem that can't be solved. In orbit there are almost vacuum so there wouldn't be any kind of cooling. We have tested the solar cells under a 2000 W halogen lamp; the voltage level dropped almost 70% in a short time, but there is a big difference between the light from a halogen lamp and the sun. The sun is far from the satellite and has a different spectrum which gives more energy in form of light then in heat.

One last problem with the solar cells is aging. Our mission is set to last for 2 maximum 6 months depending on the orbit so aging wouldn't be a problem in this project.

6.5.13 Batteries

The satellite contains 2 * 1500mAh Li-ion batteries (connected in parallel) from Danionics. Li-ion batteries are chosen because of their low weight. During the time spent in the lab, testing the batteries, only two problems occurred. They mustn't be charged with a higher voltage than 4.2V, which is the battery voltage when it's fully charged. And the battery voltage mustn't get below 3.0V; because the battery will collapse immediately. To prevent these things from happen; a couple of safety precautions where made.

To prevent the charging voltage from raise above 4.2V a 4.2V zener diode was put in parallel with the battery. If the voltage from the DC/DC converter between the solar cells and the battery should mount the zener voltage, the diode will start to conduct, and transform the redundant power into heat.

Normally this shouldn't be a problem since the DC/DC converter has a regulated output.

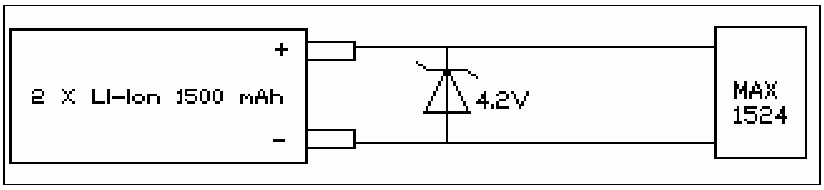

Figure 23: Picture of the zener diode in parallel with the battery. The diode will start to conduct if the voltage rises above 4.2V from the MAX 1524 DC/DC converter.

The power management is always in control of the battery voltage. So if the voltage should come close to 3.0V (3.3V) the management would shutdown all the subsystems necessary, to prevent the battery of discharging too much and to let the solar cells charge the batteries.

A problem that could occur if the solar cell area where much bigger is that the charging current could get too high. A Li-ion battery should be charged with a maximum of 0.8CmA, or in our case 2.4A. If this had been a problem, some kind of charging circuit would be used.

Except from these three examples; the Li-ion batteries are very reliable. A 1500 mAh Li-ion battery delivers 1500mA for one hour in 1000 cycles.

6.6 Electro magnetic considerations

[11]

The satellite has a lot of electronic circuits which could be damaged by electronic fields. All wires that conduct will generate electric fields, and all wires will act as antennas and be affected by the fields. Some components, transmitters, have as its main task to develop electromagnetic fields. Others as receivers are tuned to be sensitive to certain frequencies. If other circuits are working at the same frequencies as the transmitters and receivers problems can arise. This isn't a problem only with the communication circuits, all components are sensitive to different frequencies and can be disturbed/interrupted by others. This makes this subject dividend in tree; EMC (Electro Magnetic Compatibility), EME (Electro Magnetic Environment) and EMI (Electro Magnetic Interference).

6.6.1 EMC

Electromagnetic compatibility is the condition when different electronic equipment is performing along each others without suffering degradation in efficiency caused by the other part. Compatibility means how equipment is affected and prevented from operate normally by externally generated electromagnetic fields.
EMC must be taken in consideration when circuit layout is done. With a proper layout, EMC problems can be reduced.

6.6.2 EME

Electromagnetic environment is the environment surrounding all electronic equipment. All wires that conduct in the environment will be a part of creating the EME. The environment will be exposed with different frequencies with different energy density.

6.6.3 EMI

Electromagnetic interference is the connection between EMC and EME. When a product is affected by the electromagnetic fields surrounding it, interference is created. Different circuits are vulnerable to certain electromagnetic frequencies but can tolerate other. This means that EMC and EME not always create a problem. There is a problem with EMI only if a specific frequency is present, with a sufficient energy density, and there are circuits vulnerable to that frequency present.

6.6.4 Possible solutions

There are differences between electromagnetic noise emission from power and digital electrics. Digital circuits generate mainly noise at certain frequencies depending on rise times and clock frequencies. Power electronics on the other hand generates fields because of high currents in the wires. DC/DC converters, which are present in the satellite, generate noise at a range of frequencies. This is depending on the switching frequencies and currents in the wires. Filtering the noise can be a little bit harder when the noise is spread over a wide frequency area. But in the case of the satellite all noise from DC/DC converters are very high frequent. This makes it easy to filter, inductance in the wires between the DC/DC converter and the subsystem together with some capacitances will damp the noise.

Recommendations for minimizing the electromagnetic problem:

- Use a ground plane, proper grounding.
- Use low clock frequency.
- Minimize the printed area of circuit loops, specially the ones containing high frequencies such as busses and clock circuit.
- Make loops as short as possible. Small PCBs has lower emissions because of the shorter connections, long acts as antennas.
- Connect high frequent filters to all connections to the PCB.
- Shielding. This will absorb the energy in the electromagnetic field.

6.7 Grounding of stand alone systems

Grounding, in a small independent system, can be a big problem. It is easy to overlook the grounding and focus to much to one the power system. In a small system that isn't connected to earth ground, grounding is more complex. In DC systems on earth, generally the cathode is connected to ground on earth. This makes the system more stable, earth ground acts as a buffer which smoothes the currents. Ground will act as a big filter and damp ripple. This isn't the case in the satellite. Signals will be transferred via the ground system and could affect other systems. The only buffer that can smooth the currents are the batteries. This is why it's critical to separate independent ground systems, and then connect them all to the battery cathode. This is to make sure that no system will affect another by transferring signals in the ground.

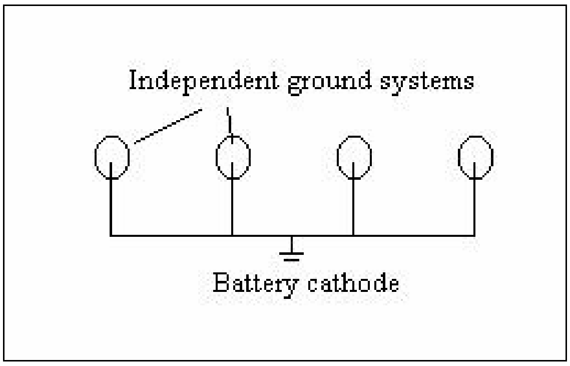

Figure 24: Right grounding. All independent ground systems are kept apart. This will make it impossible for one system to affect another.

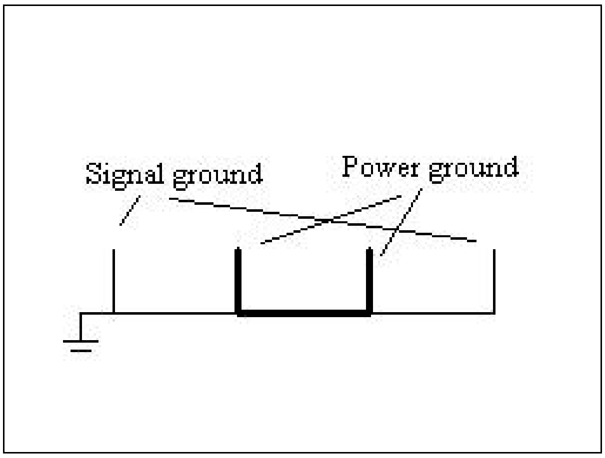

Figure 25: Wrong grounding. In this ground system power ground and signal ground share the same wiring. Power ground contains high currents and a lot of high frequent ripple. This will affect signal ground which is sensitive to that kind of signals.

The satellite has four different ground systems; power ground, digital ground, analogue ground and microcontroller ground. These systems are kept separated until they are connected to the ground plane. Ground plane is connected directly to the battery cathode. The best way to connect ground is in a hierarchic way (not in cascade). In this way ground signals are prevented from disturbing other systems.

Power ground
Power ground is the ground system that connects all DC/DC converters on the power PCB. It is natural to use a separate ground system because of the separate power PCB. In this way high frequent switching noise from the converters is kept out of the power management PCB.

Digital ground
All digital circuits has its own ground system. This is because the digital circuits could be sensitive of signals in the ground system, caused by f ex the converters.

Analogue ground
There are some analogue circuits in the satellite, such as the LDRs. These circuits are very sensitive and need to have separate grounding.

Microcontroller ground
The microcontroller has a separate ground system. This could probably be connected to the digital ground system, but for safety reasons it has its own.

Ground plane
The ground plane has two tasks; to shield and to connect the different ground systems. The shielding is made by placing the ground plane between the power PCB and the power management PCB. In this way the plane absorbs the energy in the electromagnetic fields caused by f ex the DC/DC converters. The ground plane is connected directly to battery cathode. This makes this point ideal for connecting the different ground systems. The batteries will always act as a big capacitance and prevent signals from being transferred.

6.8 Redundancy

Because this is a small satellite redundancy has been nearly neglected. The satellite could only measure 10*10*10 cm and 1 kg. In this satellite there are several receivers, transmitters, batteries, antennas and the gravity boom.

There is some redundancy; the nicrome wire that should handle the boom and the antenna release has a double circuit which is controlled separately. The antenna release must be infallible because it's a key operation for this mission.

The satellite also contains of 2 single cell 1500 mAh Li-ion in parallel. If one of the cells quit on us, the voltage level will be the same; but the storage capacity will be reduced by 50%. If for some reason both batteries should malfunction; the solar cells would be able to run some of the systems directly.

The reason why it was decided to use a battery bank of 3000 mAh was in a case of a "worst case scenario" the satellite will go in orbit upside down and none of the solar cells where able to charge the batteries. Other possibilities are that the solar cells get crushed during launch (or in orbit) and therefore would not be able to deliver power. Or the DC/DC converter between the solar cells fails. The batteries will anyway be able to perform the success criteria.

The power management unit will continuously check the system for errors. If necessary turn on and of subsystems. If the PMU should fail; the OBDH could override the PMU through XOR gates controlling the enable pin on the DC/DC converters. The OBDH could be override by the telecommand on message from the ground station.

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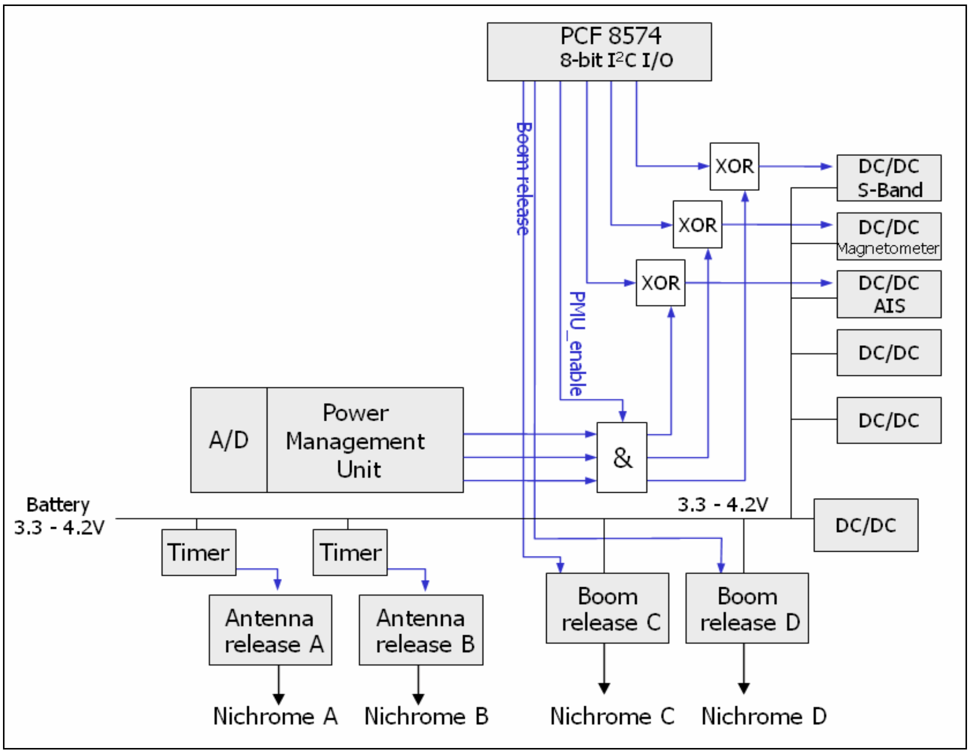


Figure 26: Shows that the DC/DC converters are controlled by two signals. It also shows the redundant release of the antennas and the gravity boom.

6.8.1 Suggested redundancy for the DC/DC converters

All of the DC/DC converter could be weak points in the satellite. In fact all the DC/DC converters are weak points because all of the subsystems are fed through one. If they fail the power could be blocked, or just go straight through unregulated and destroy the subsystem. Therefore redundancy is to prefer. But again; the system is bound by limited space.

Some of the DC/DC is alone delivering a single output voltage (Magnetometer 6.5V and S-band 5.5V). A possible way to make redundancy for these converters is to use an n-type MOSFET with the gate attached to the out put pin on the origin DC/DC converter. If the DC/DC out put signal turns to zero; the MOSFET will start a redundant DC/DC converter with the same output voltage. The redundant DC/DC converter will remain unused nothing fails.

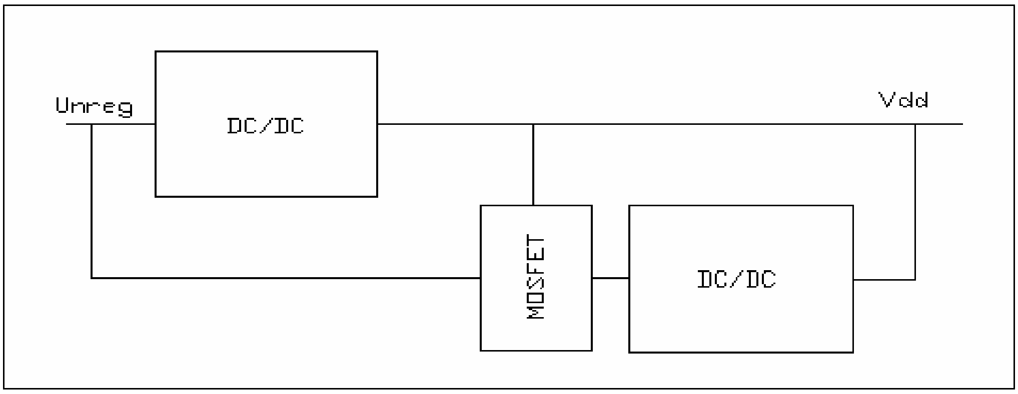


Figure 27: Shows a redundant DC/DC with a MOSFET switch that will

6.8.2 DC/DC between solar cells and the battery

There are two DC/DC converters on the nCube satellite power supply that are considered more important then the other. This is because they are essential whether the launch is a success or not.

The DC/DC between the solar cells and the battery is one of the more important. It's very essential because the solar cells are the only way of getting energy. When this DC/DC was constructed, one that could handle almost twice the current that the solar cells can deliver was chosen. There are two external MOSFET, diodes and inductors to be able to cope with the power for charging the batteries. This DC/DC can deliver over 1A to charge the batteries when transforming from 3.0V to 4.2V.

The redundancy for this system could be solved as mentioned above. However if the charging system should fail the batteries have a capacity of 3000 mAh, which will last for about 10 orbits; and the launce could still be a success; even if the redundancy system is neglected.

Consumption	**-991,5**	**[mWorbit]**
Payload turned off	**-512,4**	**[mWorbit]**
From solar cells	**1232,3**	**[mWorbit]**
Battery capacity	**4856,3**	**[mWorbit]**

Figure 28: Shows the power consumption (normal operation) with and without the subsystems switched on. It also shows the power delivered from the solar cells and the battery capacity.

6.8.3 Suggested redundancy for the DC/DC supplying the "hard wired" systems

The weakest point in this system and the most important DC/DC; is the single DC/DC converter the supplies all the "hard wired" subsystems as well as OBDH and the PMU. If this single converter fails, the whole satellite would be considered dead. A redundant system should be implemented.

One way to solve this problem is to connect a schotky diode between the output signals from two DC/DC converters with the same output voltage. This is very simple and efficient way to of solve this problem. If none of DC/DC converter fails; the system would work as normal and the diode would block. If one of them fails the potential over the schotky diode would be Vout and the diode will start to conduct. Both systems will again be supplied with the correct voltage. One thing to have in mind is that the DC/DC converter must be able to handle the load from both subsystems.

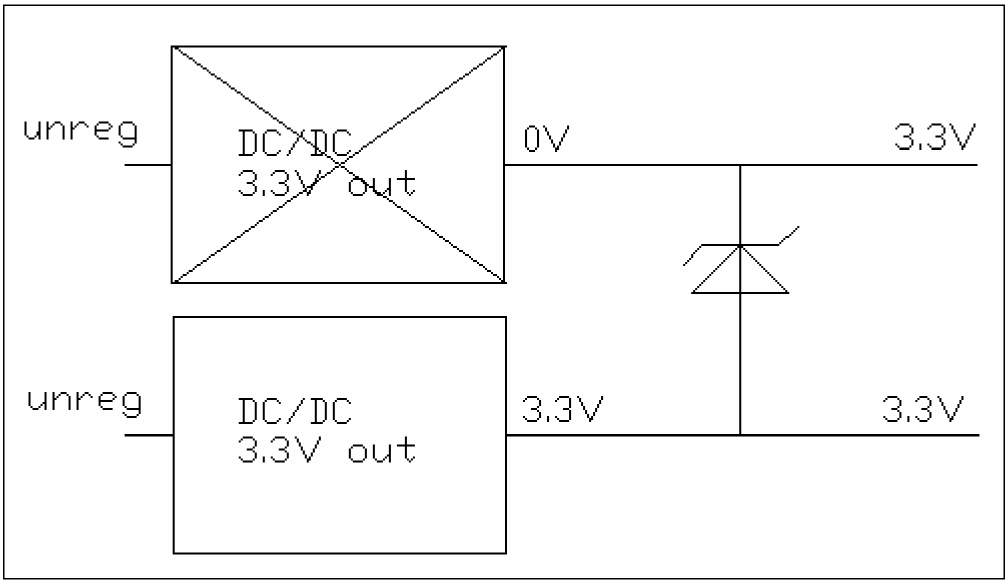


Figure 29: Shows a redundant solution for the DC/DC converter supplying the "hard wired" systems.

Instead of using redundant solutions it's possible to couple two or even three DC/DC converters to supply each sub system. This is called load splitting. Our design uses load splitting; but only one converter supplying each system. As mentioned under DPS each of the converters must be designed to handle all the power alone; because the load on the converters will be put on the one with the highest output voltage. If one or two of the three converters fails the system will still be supplied. When using several converters in parallel the stress on each could be reduced hence the reliability will increase. The problem with this is more power consumption, more source of failure in hard/ software and the space to place the components on.

7 Satellite construction - Practical part

7.1 DC/DC converters

7.1.1 MAX1524 step-up converter

To be able to charge the batteries a MAX1524 step up converter is used. The solar cells voltage is about 3.4V and the charging voltage is 4.2V. The solar cell voltage is determined by the number of cells. There is a possibility of using more cells to rice the voltage and skip the converter. But the behavior of the cell voltage is not suited for charging directly. The cell voltage is depending of the angle between the sun and the cell surface. This makes it hard to optimize the charging without using a DC/DC converter. The best situation is to always have 4.2V from the cells even thou the sun angle is big. This is possible with the converter. The solar cell voltage will vary between ~1.5 and 3.4V, the converter boosts the voltage to 4.2V. The charge voltage cannot exceed 4.2V in order to spare the batteries. This is why a zener diode is placed after the converter in order to ensure this.

The converter that is used after the solar cells needs to handle big currents. The MAX1524 can handle up to 1500mA input current which is acceptable. The converter needs to be able to operate with a low input voltage (because of the solar cell voltage). The MAX1425 can operate with an input voltage of about 1.5V, depending on the load. A problem with the converter is that it can be hard to start it. The input needs to be about 3V for the converter to start. If the battery is connected on the output, the converter operates more stable and the input can be driven lower. Once the converter is started, it operates well, but this is a problem that needs to be solved anyway.

There is no possibility to turn of turn of the converter. There are no reasons for turning the converter off and the converter needs to be as fail safe as possible. If an enable pin where used and the PMU malfunctions and turns the converter off, the charging stops.

The efficiency of the converter is acceptable. It is hard to find converters that can handle big currents and maintain a good efficiency.

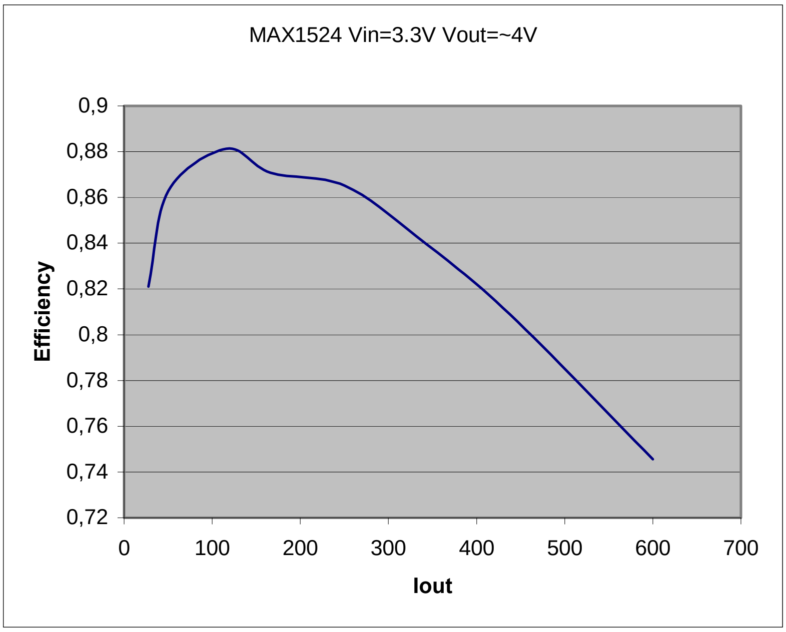


Figure 30: Efficiency of MAX1524. Vin=3.3V, Vout is varying from 4.20 to 3.8V.

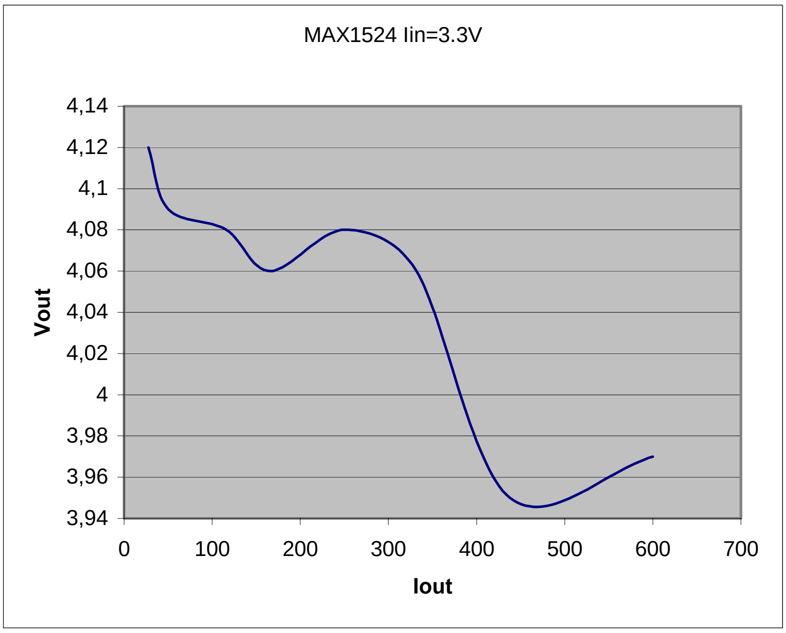


Figure 31: Output voltage of MAX1524. The output is depending of the load current.

A problem with the converter is that the output voltage is depending on the load current. This is not supposed to happen; the regulation of the output is not working properly. This can be compensated for by choosing a higher charging voltage. In this case the charging will work good only if the battery voltage is lower then the charging voltage.

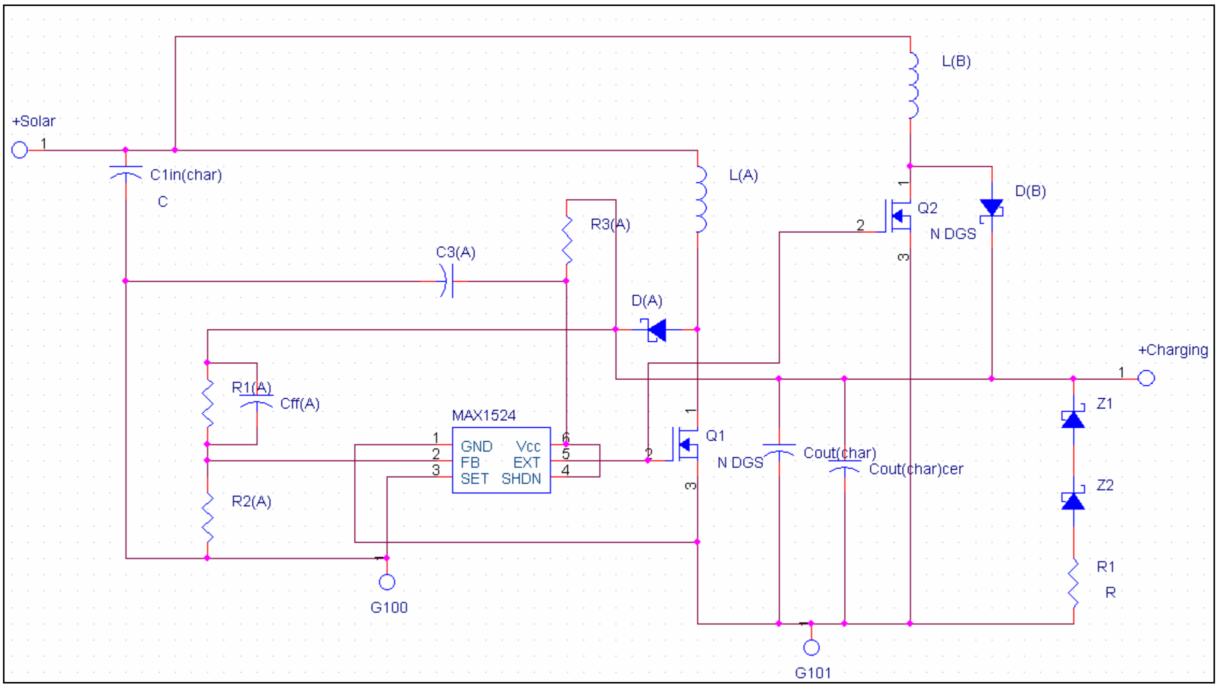


Figure 32: The circuit layout to the MAX1524 DC/DC converter, with a 4.2V output. There is a zener diode attached on the output to ensure that the voltage don't raise above 4.2V.

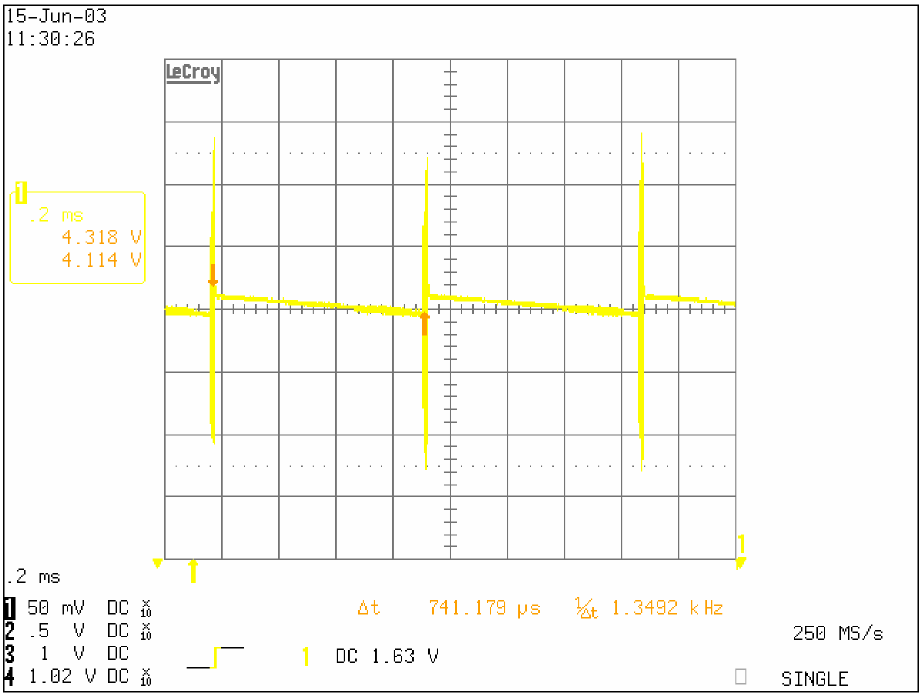


Figure 33: Output voltage of MAX1524. Vin 3.3V, Vout 4.2V. No load is connected.

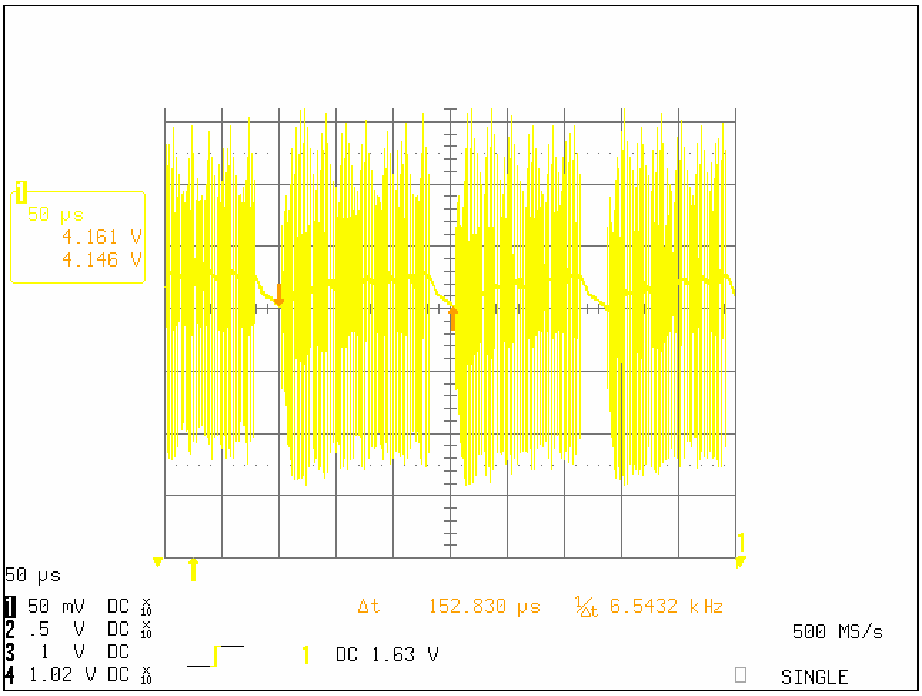


Figure 34: Output voltage of MAX1524. Vin=3.3V, Vout=4.2V. 268mA load current.

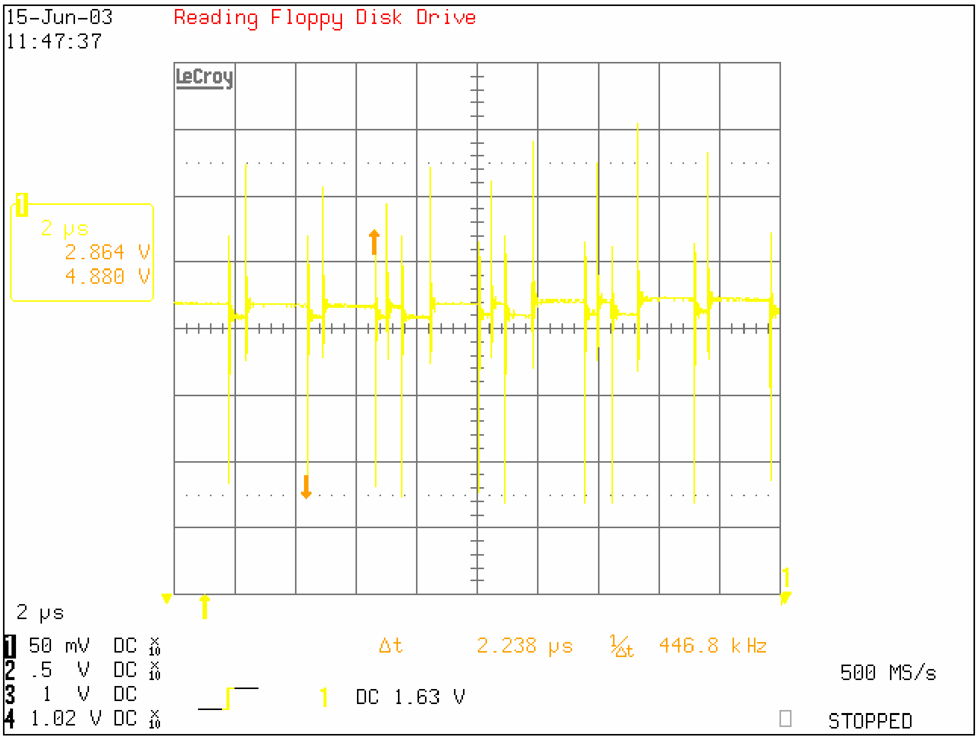


Figure 35: Output voltage of MAX1524. Vin=3.3V, Vout=4.2V. 268mA load current. Picture of ripple.

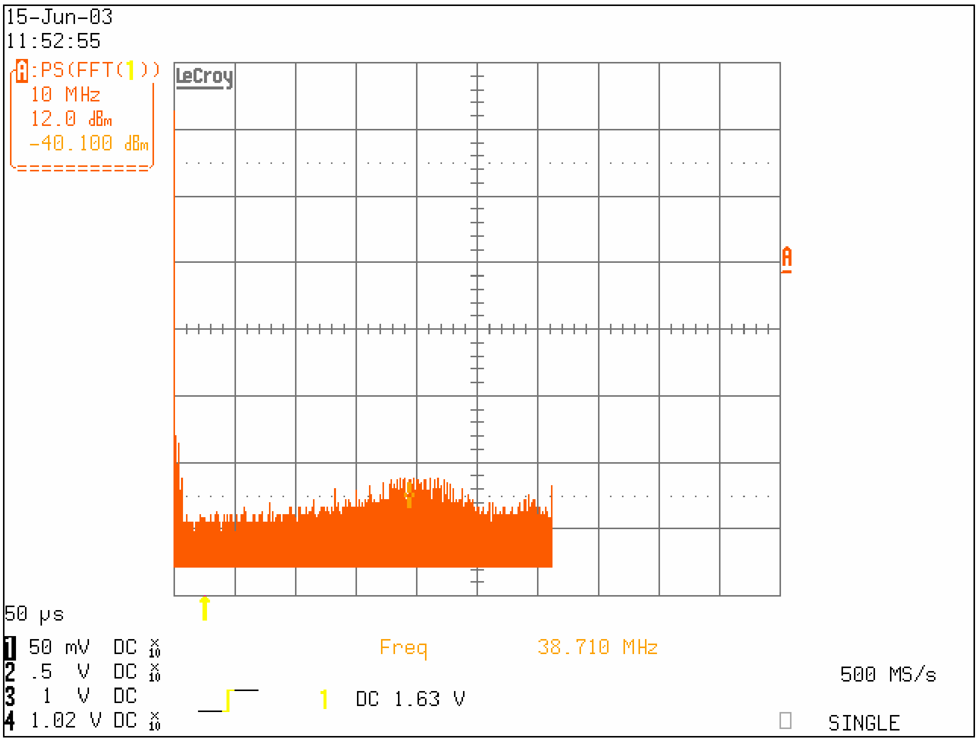


Figure 36: Output voltage of MAX1524. Vin=3.3V, Vout=4.2V. 268mA load current. Spectrum analysis.

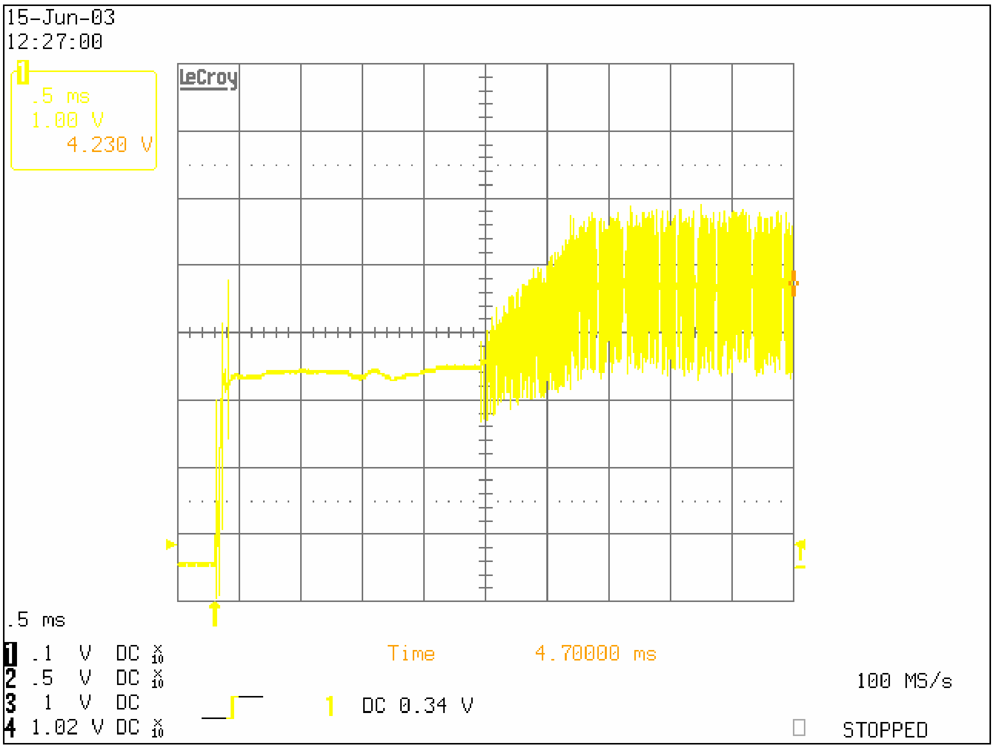


Figure 37: Output voltage of MAX1524 during startup. Vin=3.3V, Vout=4.2V. 268mA load current. Startup time 6ms.

7.1.2 MAX1896 step-up converter

The satellite has two different subsystems with voltage levels higher then battery voltage. Tests have shown that the MAX1896 step-up converter is suitable for these applications. It is a simple converter with few external components. The S-band transmitter needs 5.5V and the magnetometer 6.5V. The unregulated battery voltage is between 3.3 and 4.2V so the converter boosts up the voltage as well as stabilizing it. The S-band converter needs to handle rather big currents, 400mA. The problem with converters is that their efficiency drops when the currents gets higher. The MAX1896 handles 400mA with an acceptable efficiency.

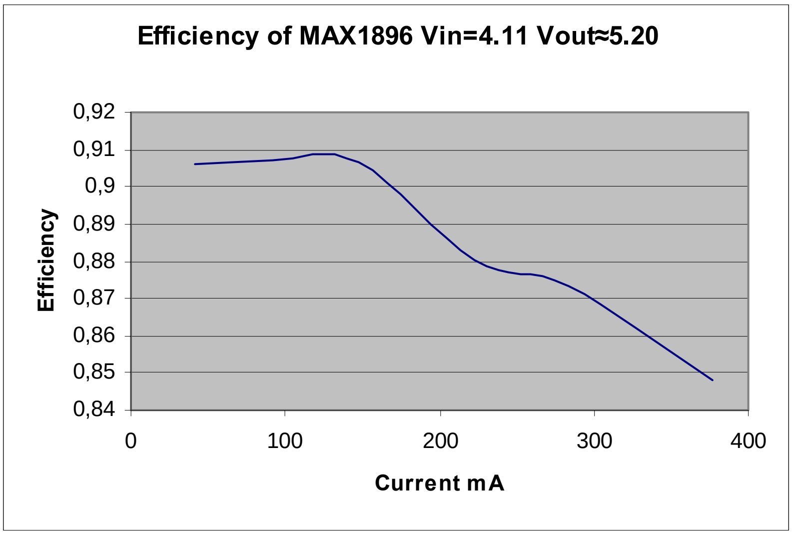


Figure 38: Efficiency of MAX1896, V_{in}=4.11, V_{out}≈5.20

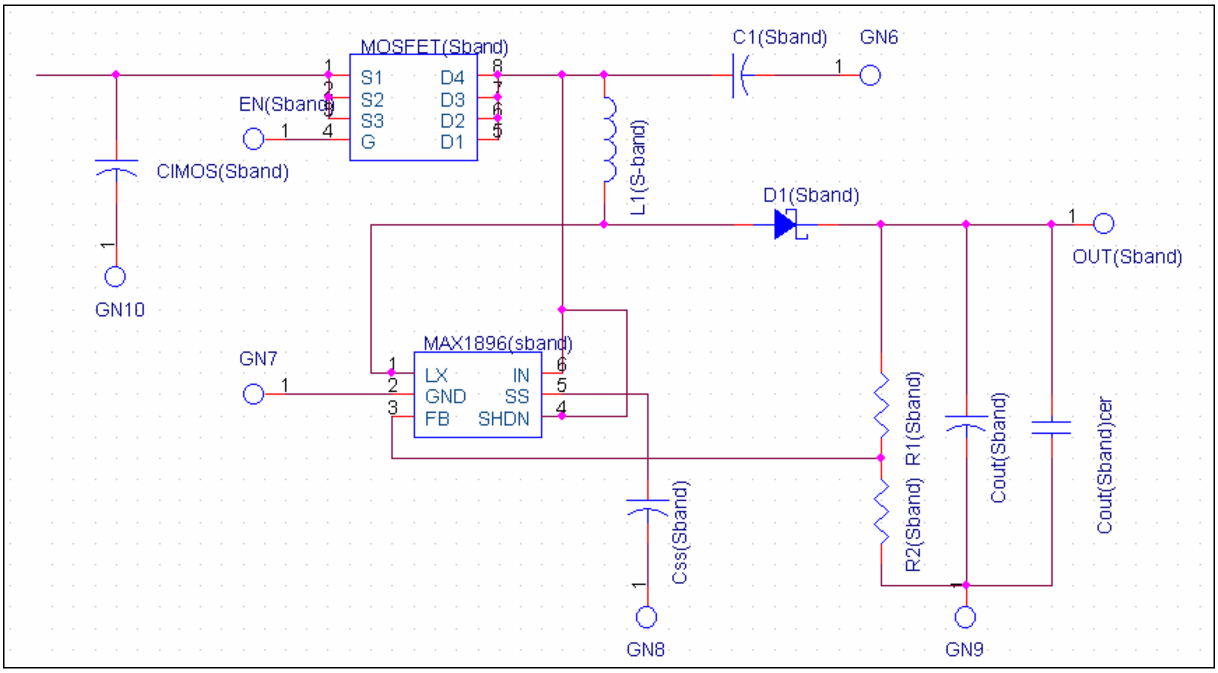


Figure 39: The circuit layout of the MAX1896 DC/DC converter with a 5.5V or (6.5V) output voltage. There is also a MOSFET ensuring true shut down.

The two resistances determines the output voltage. The converter can be set to a value between V+ and 18V. There is a 0.1uF ceramic filter capacitance connected to the output. This is used to filter the high frequent ripple. There is still ripple on the output but it has a very high frequency >120 MHz. The inductance in the connections to the subsystems together with a filter capacitance on the input of the subsystems will probably reduce that ripple. There has to be tests made when the satellite is fully assembled.

The S-band transmitter and the magnetometer shall be able to be turned off. This is made by turning the converter off. The converter has an enable pin but that pin isn't a true shut down. It only turns off the switching in the converter; the output will still be the input voltage. The solution to the problem is to use a p-channel MOSFET transistor together with the converter. The MOSFET doesn't affect the efficiency because of its low resistance. The gate is used as a enable pin.

In the tests made, output voltage is set to 6.6V. The behavior and the characteristics of the converter is almost the same using 6.6V or 5.5V output. The start up time is a little less using 5.5V output. The efficiency drops when the output gets higher.

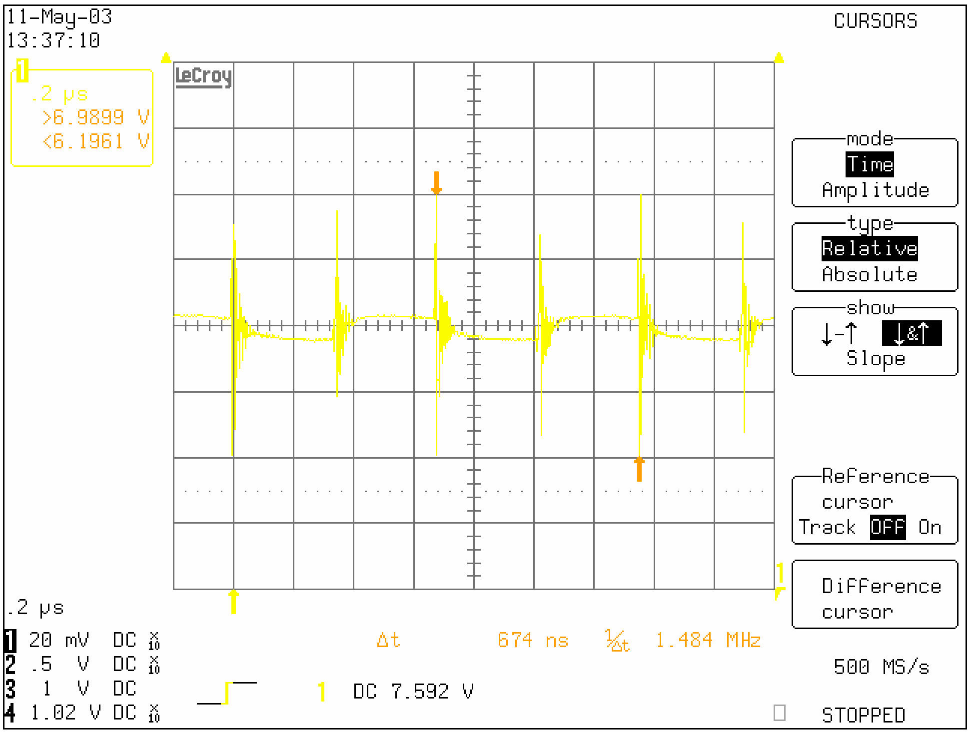


Figure 40: MAX1896. Output ripple between 7 and 6.2V. 166mA load current, test is made with a ceramic 0.1uF output filter. Converting from 3.6 to 6.6V.

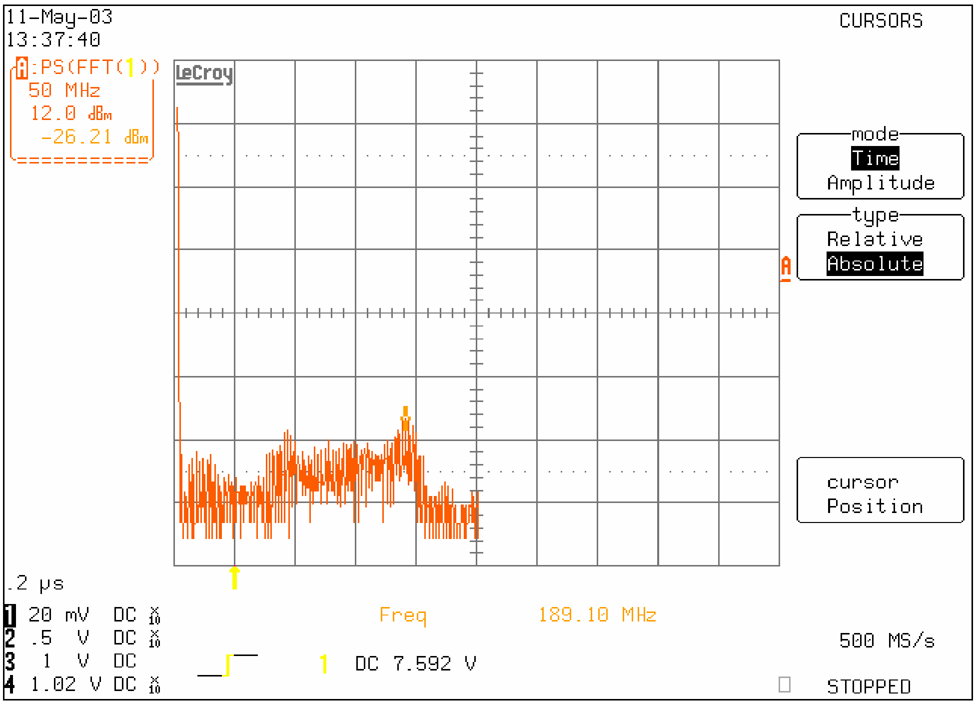


Figure 41: MAX1896. Frequency spectrum. 166mA load current, test is made with a ceramic 0.1uF output filter. Converting from 3.6 to 6.6V.

As seen in figure, there are high frequencies present even with an output capacitance. This will be filtered by the inductance in the wires to the subsystem and by the input capacitance of the subsystem.

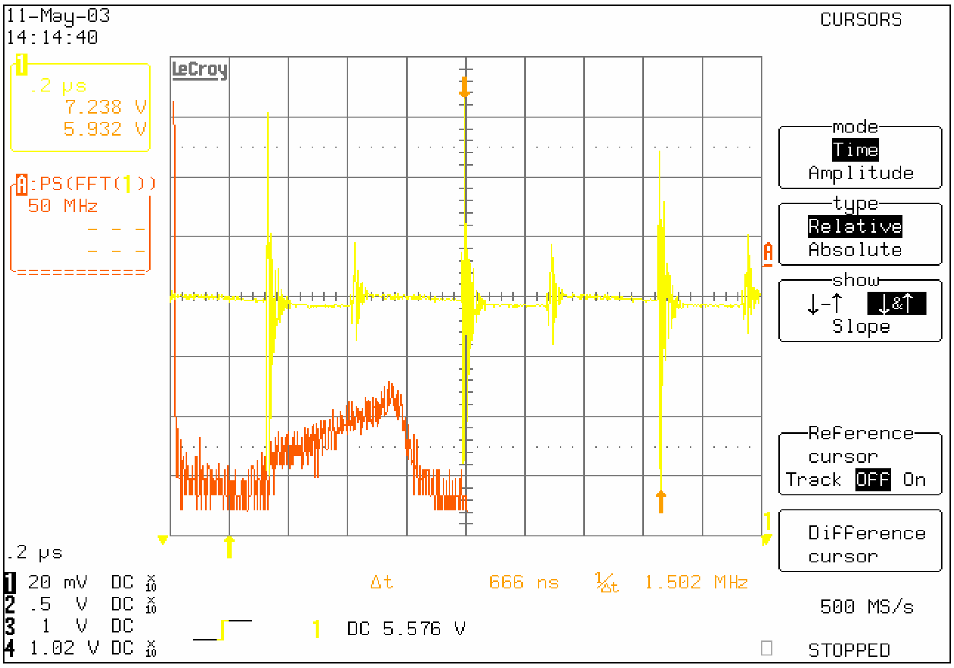


Figure 42: MAX1896. Output ripple without the ceramic output filter; between 5.9 and 7.2V. 70mA load current. Converting from 4 to 6.6V. Note the high amount of high frequency ripple.

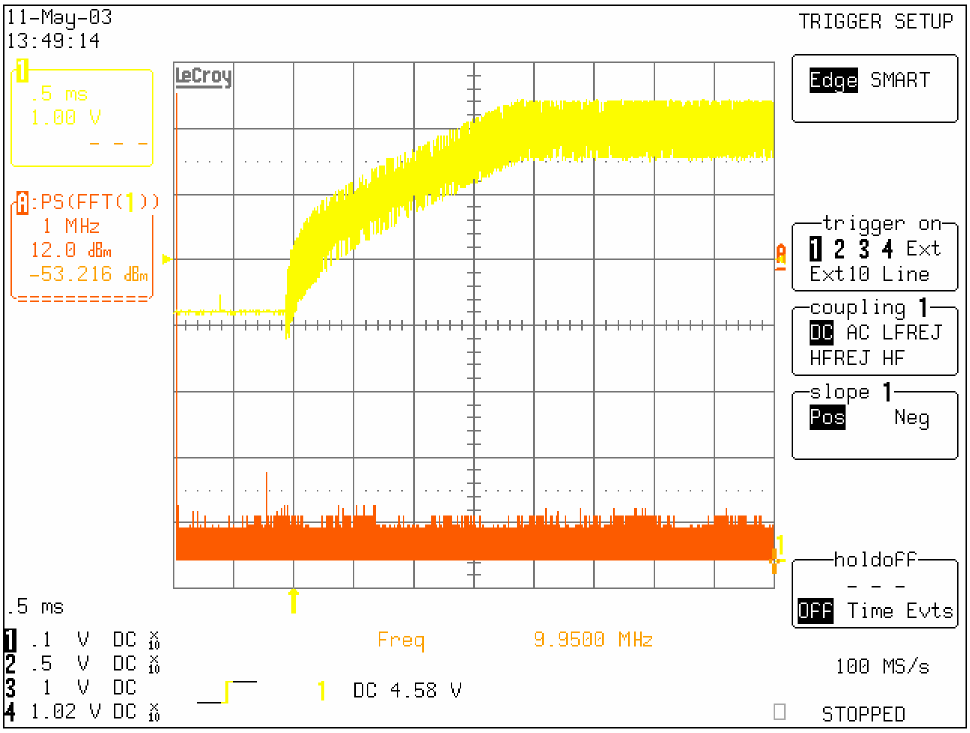


Figure 43: MAX 1896. Converter start up to 6.5V. 40mA load current. Start up using enable pin. A ceramic output filter is used. Start up time is 2ms.

Note that when the converter is used without the MOSFET; the output voltage equals the input even as the enable pin is off.

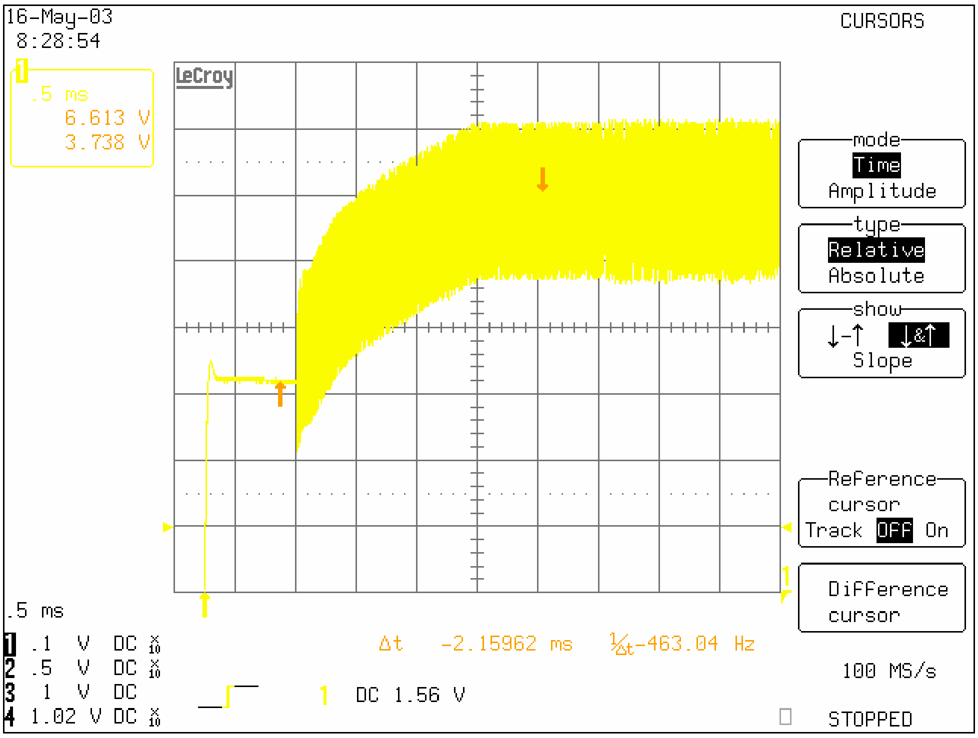


Figure 44: MAX1896, Start up using a MOSFET. Output voltage goes from 0 to 6.6V via 3.7V (V_{in}) for a period of time. Start up time is 2.5ms.

In this case the MOSFET is used. There is no voltage fall in the transistor. This makes the MOSFET ideal for turning the converter on and off.

7.1.3 The TPS62003 step down converter

To be able to use lower voltages than the battery a step down converter is used. The satellite has a number of subsystems requiring 3.3V. For this purpose a TPS62003 step down converter from Texas is used. It is a small high efficiency step down converter. It cannot handle big currents (max 150mA with V_{in}=4V). But it is enough for the applications in the satellite.

V in [V]	I in [mA]	V out [V]	I out [mA]	Efficiency
4	8,9	3,326	10	0,934
4	22,01	3,321	25	0,943
4	43,9	3,320	50,2	0,949
4	85,9	3,240	100	0,943
4	106,9	3,201	125,5	0,939
		Break	150	
3,5	9,91	3,324	10	0,958
3,5	24,49	3,325	25	0,970
3,5	48,1	3,284	49,6	0,968
3,5	97,6	3,290	100,1	0,964
3,5	121,7	3,299	123,9	0,960
3,5	148,7	3,306	150,5	0,956
3,5	200,3	3,332	200	0,951
3,5	250	3,285	249,8	0,938
3,5	301,8	3,236	301,7	0,924

Figure 45: Table of efficiency of the TPS62203 DC/DC converter.

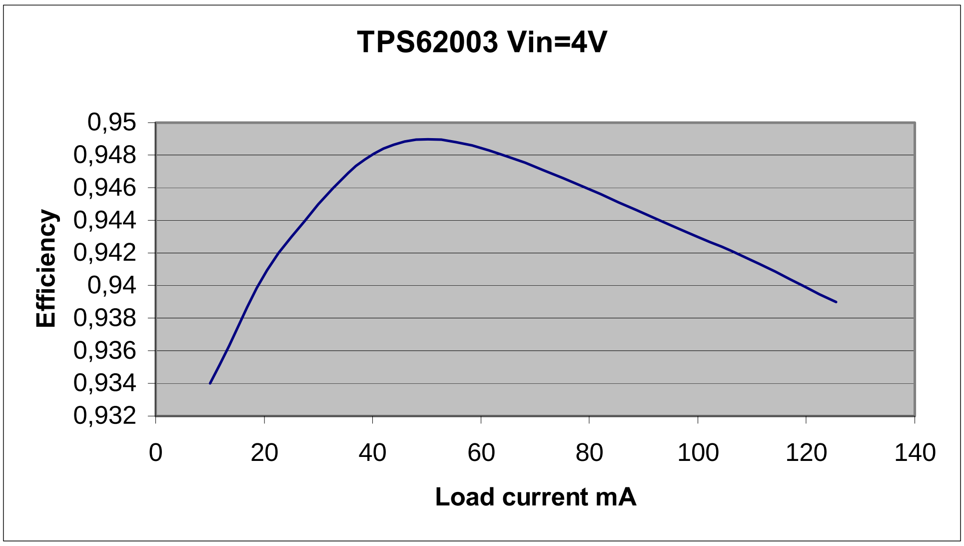


Figure 46: Efficiency of TPS62003. Max efficiency ~95% at 50mA.

All the applications that need 3.3V have about 40mA load current. This converter is ideal to use, it has a good efficiency from 20 to 120mA. One system, the AIS receiver, shall be able to be turned off. This is done by the enable pin. This is a true shutdown pin meaning that when it is turned off the output is 0V.

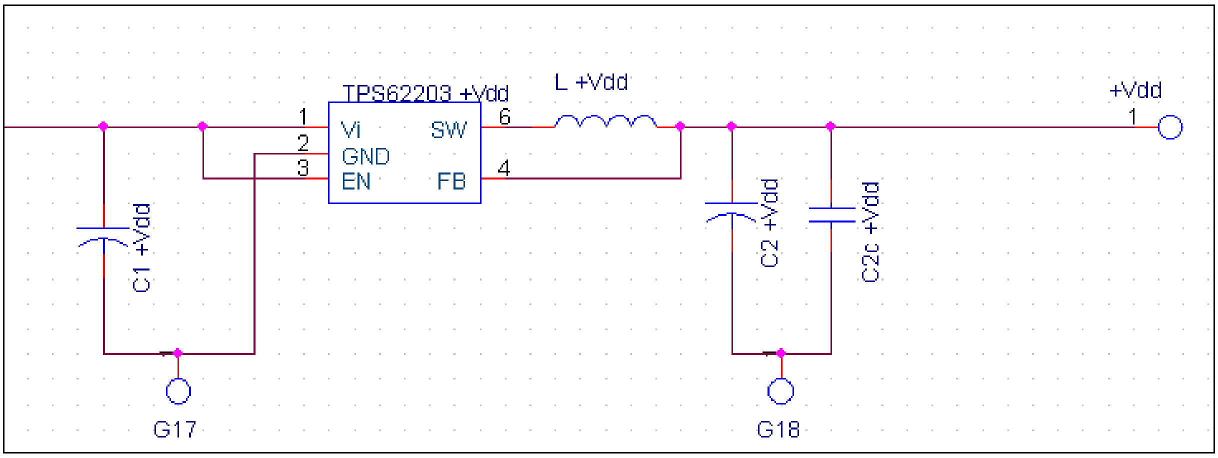


Figure 47: The circuit layout of the TPS62203 DC/DC converter with a 3.3V output.

The TPS62003 has a fixed output, preset on 3.3V. That results in fewer external components. The input can range between 0.7 and 8V which suits the battery voltage. There is used a 0.1uF ceramic capacitance to filter the output.

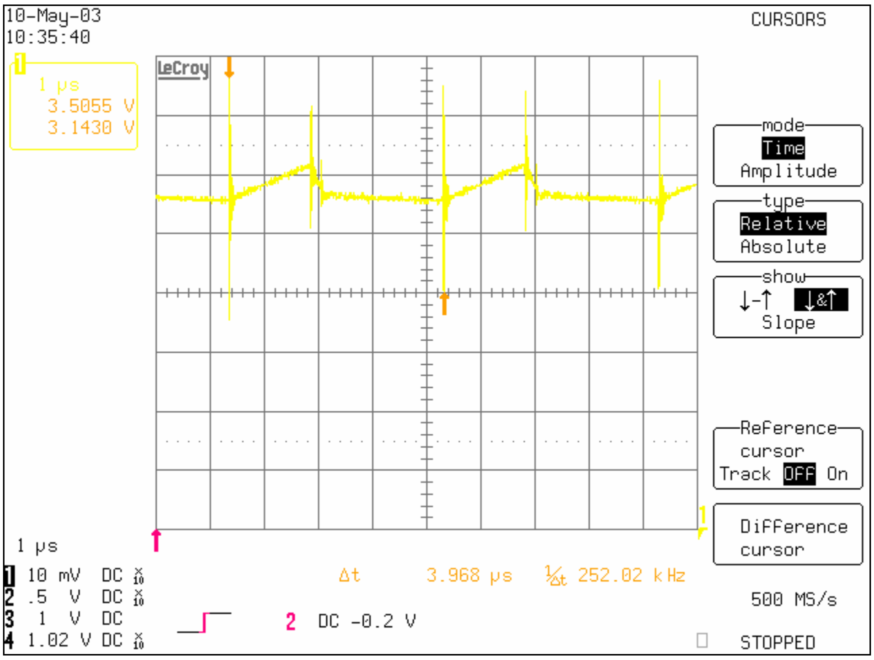


Figure 48: Output ripple between 3.14 and 3.5V without output filter. 20mA load current. Converting from 4 to 3.3V. Switching frequency is 252kHz.

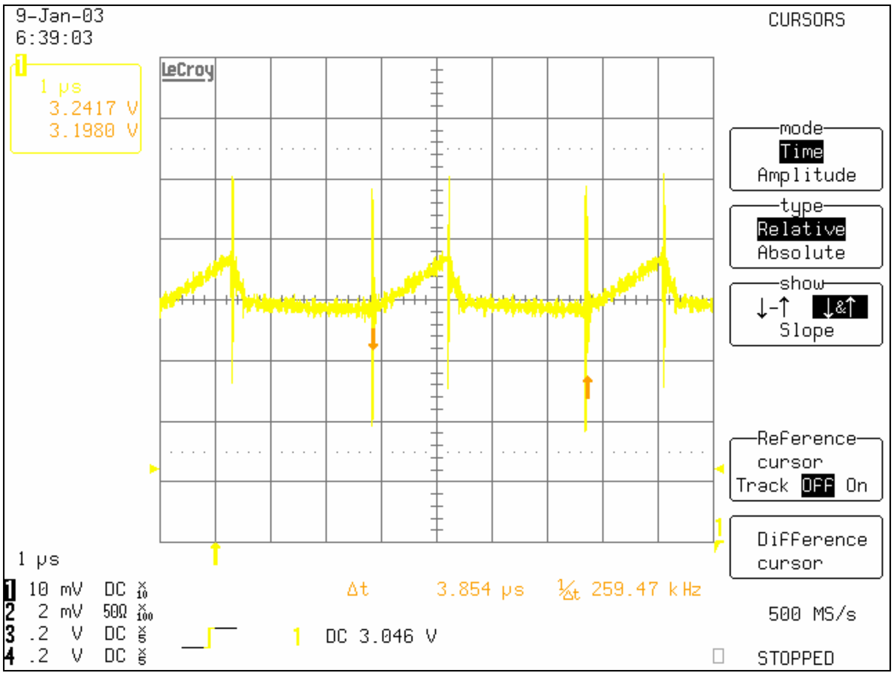


Figure 49: Output ripple between 3.14 and 3.5V using an output filter. 20mA load current. Converting from 4 to 3.3V. Switching frequency is 259kHz.

The output filter does not filter the high frequent ripple. The inductance in the wires to the subsystem together with an input filter will probably solve the problem. More tests have to be made on this issue.

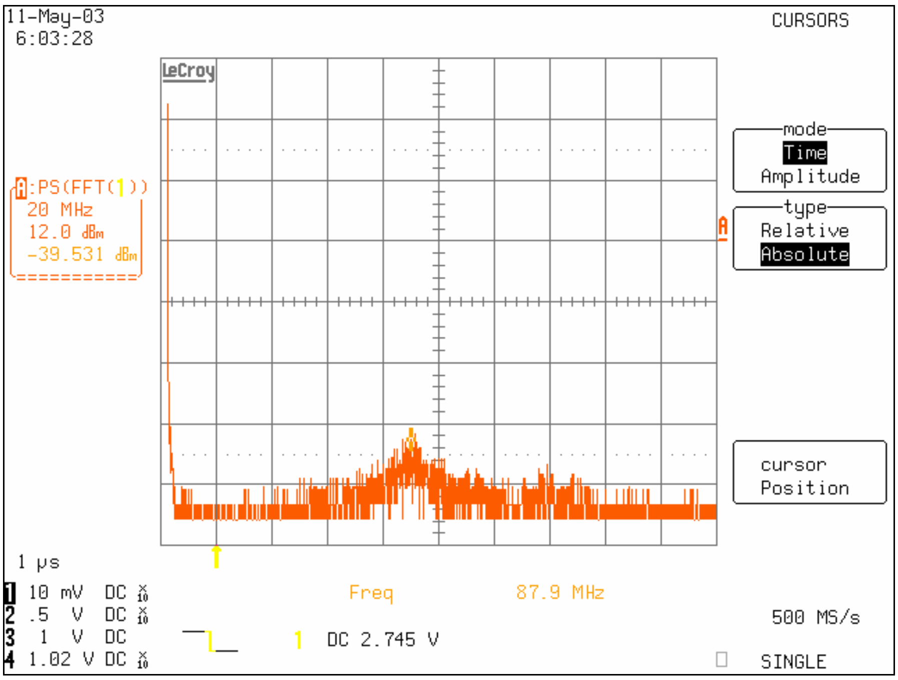


Figure 50: Frequency spectrum of TPS62003. 20mA load current converting from 4 to 3.3V without input filter.

As seen in figure; high frequent ripple is present. This will be filtered by capacitances on the output of the converter and the input of the subsystem as well as by the inductance of the wires.

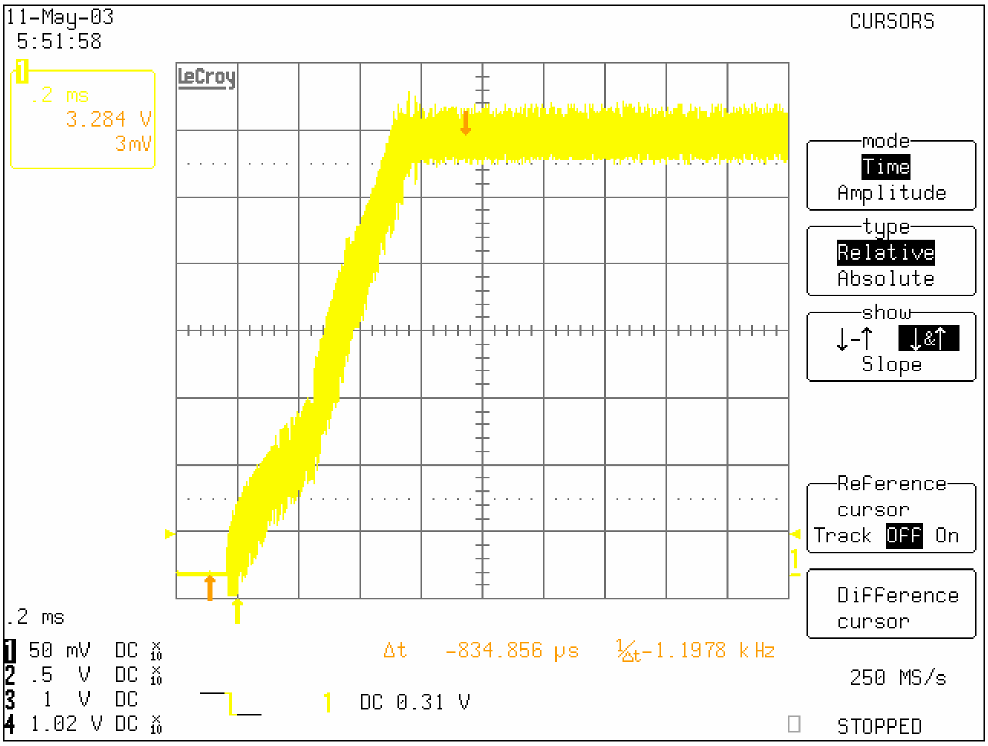


Figure 51: Start up of TPS62003 with 20mA load using power supply pin. No output filter is used. Converting from 4 to 3.3V. Start up time is 6ms.

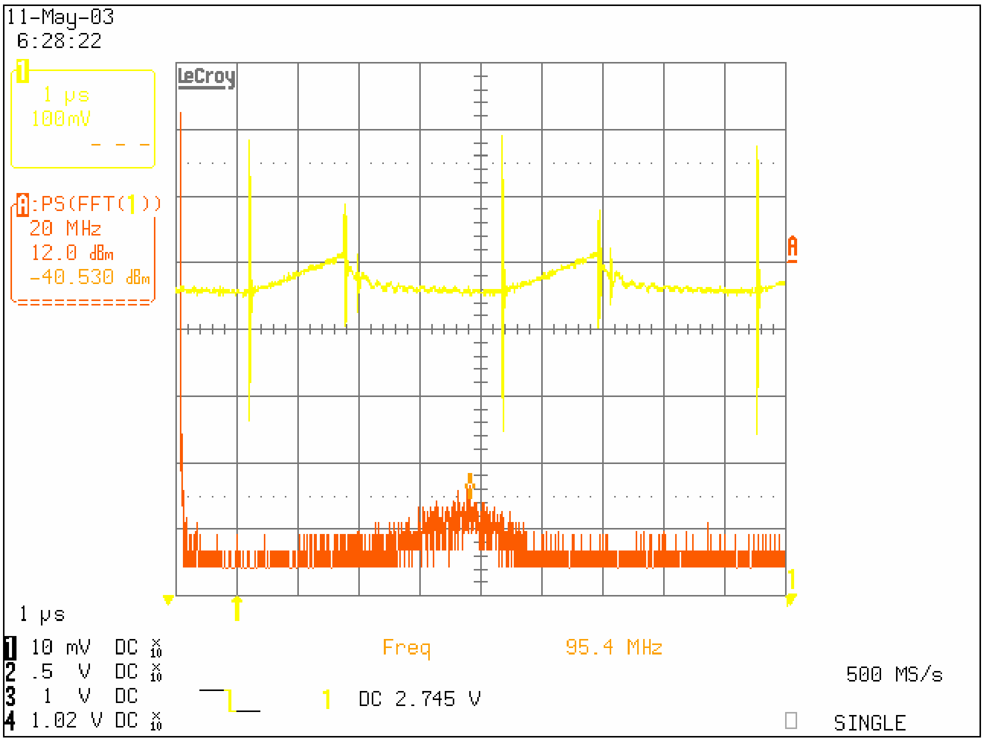


Figure 52: Output ripple and frequency spectra of TPS62003. Converting from 4 to 3.3V with 20mA load. Output is filtered with a ceramic 0.1uF capacitance.

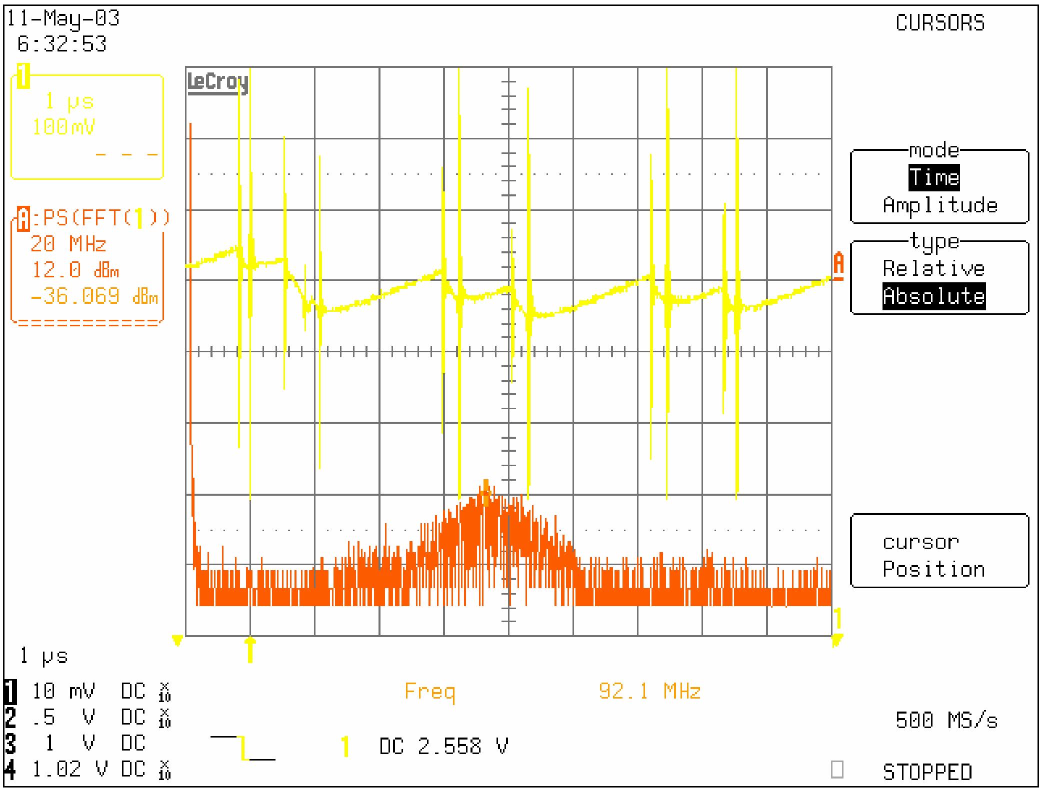


Figure 53: Output ripple and frequency spectra of TPS62003. Converting from 4 to 3.3V with 113mA load. Output is filtered with a ceramic 0.1uF capacitance.

The two figures above shows the behavior of the output ripple when the load current gets higher. The ripple has higher amplitude with bigger load but the frequencies are about the same. That makes it possible to use the same filter independent of the load current.

7.2 Solar cells

The solar cells used on the satellite are monocrystalline single junction cells. During the testing polycrystalline cells have been used. They have a little less efficiency but the same characteristics as the monocrystalline. The monocrystalline cells have an efficiency of about 18% and a cell voltage of 0.5V. There are cells available on the market with a much higher efficiency; triple junction cells, 30%. These cells are very expensive and are delivered in standard sizes. There is a big advantage if the cells can be ordered in specified sizes. This will make it possible to cover as much as possible of the satellite surface.

The solar panel consists of six solar sells connected in series. This will give a panel voltage of about 3.0V. The area to be covered with solar panels is 80*84mm. Every cell will have a size of 80*14mm. The cells are supplied by the University of Oslo. This will save a lot of money to the nCube project. The energy from the cells will not be limited that much compared to using expensive triple junction cells because of there standard sizes.
The solar panel voltage is about 3.0V. The batteries need 4.2V to be able to be charged. This makes it necessary to boost the voltage using a DC/DC converter. A MAX1524 converter is used for the reason. It is set to deliver a regulated output of 4.2V. To use a system like this a charger is unnecessary. The solar panels will limit the charging current and the DC/DC converter will regulate the charging voltage.

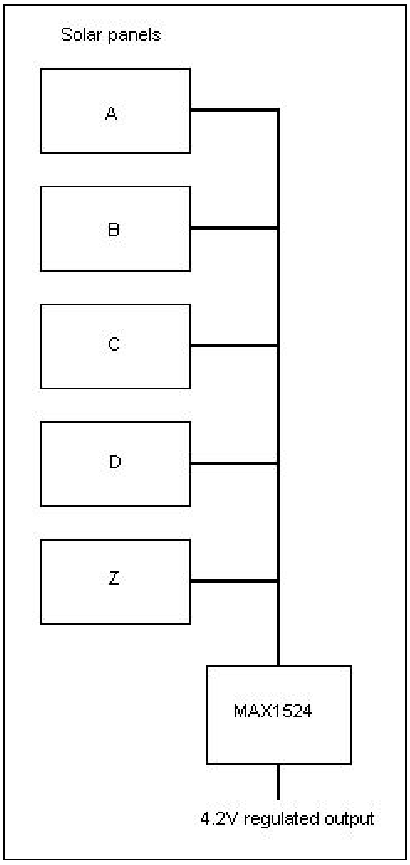


Figure 54: Solar panels connected in parallel.

The panels are connected in parallel. The cells acts as a diode with a reverse break down voltage of the cells output voltage. This means that if one series of cells is in the sun and another one is in the shadow, the one in the shadow will drain some current from the one in the sun. But when the cells are heavily loaded the solar cell voltage will drop; hence the reversed current between the cells will decrease. If the solar cell voltage gets higher it's a indication of little load which means that the batteries are fully charged. The reverse currents will increase but this does not matter because this power is redundant.

Creating the solar array

When the solar cells are been mounted its important glue them and hard them in vacuum. This is to avoid air in the glue that will explode when exposed to vacuum. The solar cells mounted and tested in this report where glued with electrical leading glue directly on a PCB which also is the physical sides of the satellite.

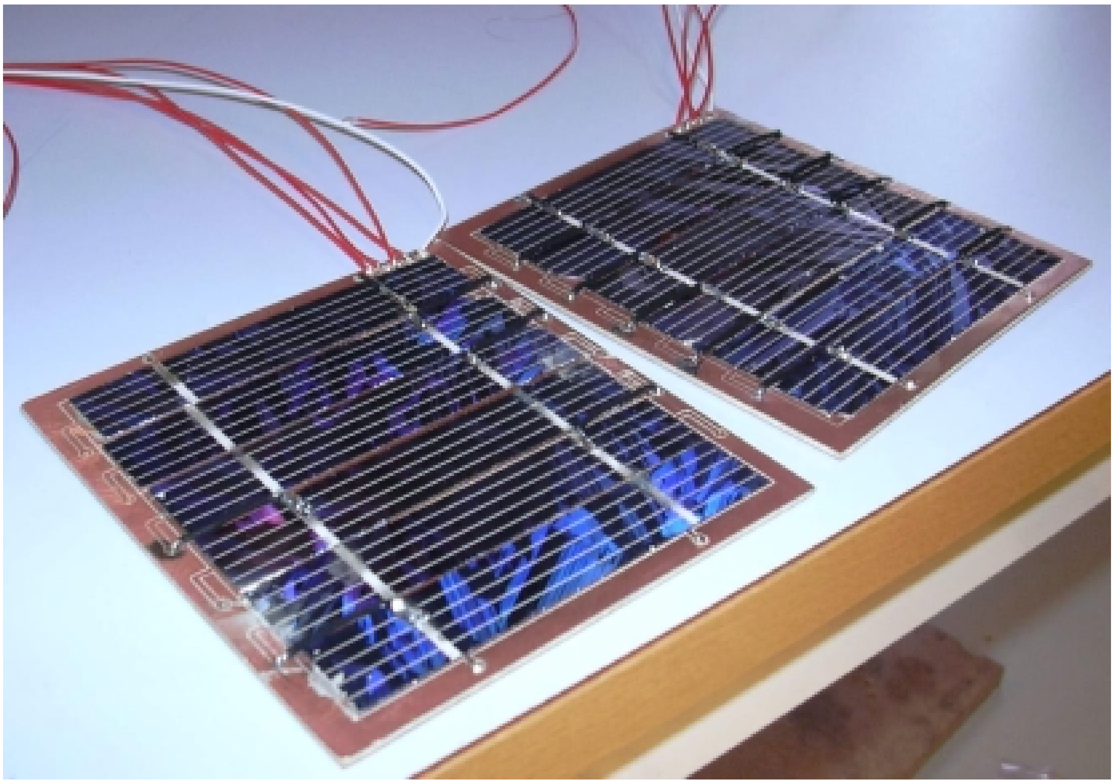


Figure 55: Picture of two solar panels.

7.2.1 *Solar calculation*

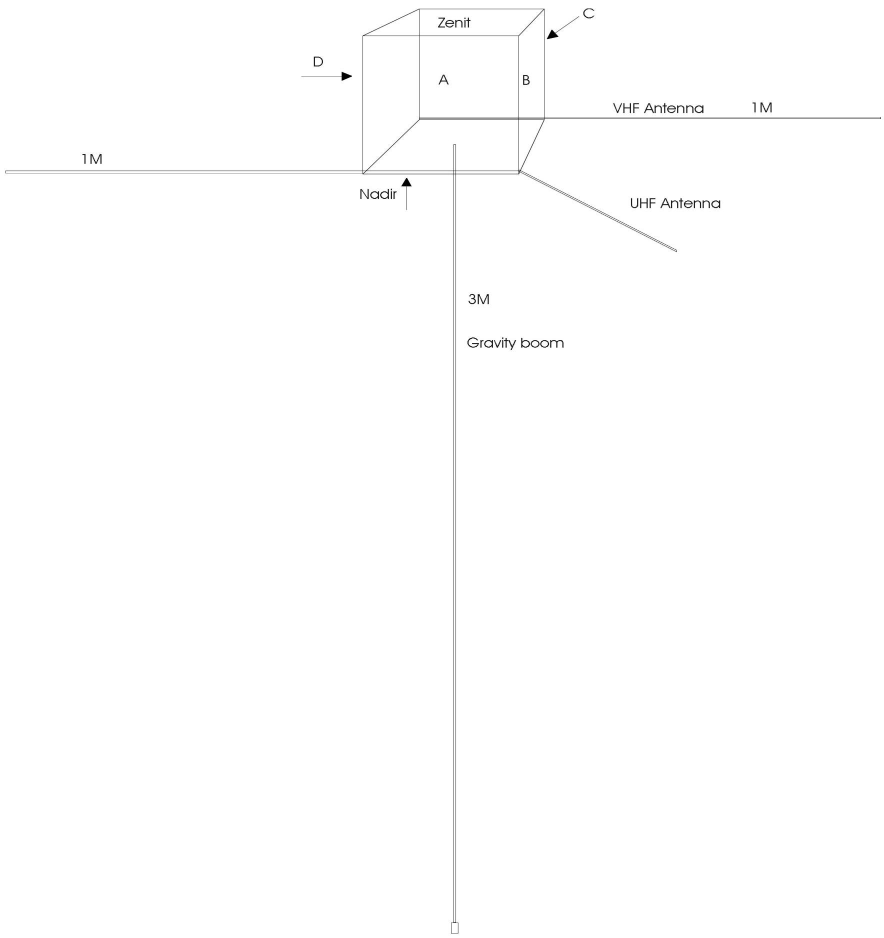


Figure 56: Shows a graphic description of the nCube satellite.

Description	Energy [W/m2]	Area [m2]	Efficiency	Angle	Power [W]	Voltage [V]	Current [A]
Nadir (45°) + A (45°)	1352	0,00672	18 %	0,7071	1,15639	3	0,38546
A (90°)	1352	0,00672	18 %	1,0000	1,63538	3	0,54513
A (45°) + B (45°)	1352	0,01344	18 %	0,7071	2,31278	3	0,77093
A (35°) + B (35°) + C (35°)	1352	0,02016	18 %	0,5736	2,81404	3	0,93801

Figure 57: Simple calculation of the energy of the solar panels.

If average powers from the 4 different states are used, 1,97965W will be available, after the DC/DC converter of 80% efficiency 1,4847W. If the satellite is orbiting 16 times/day, one orbit will last 96 minutes. The maximum time in shadow pr orbit is 16 min. That leaves the satellite 83% of the orbit in the sun. The average power from the solar cells after DC/DC is approx. 1,2323W.

Description	Efficiency	Power [W]
From solar cells		1,97965
After DC/DC	75 %	1,4847
After average orbit calculation	83 %	1,2323

Figure 58: Available energy from the solar panel after the DC/DC converter is 1,2323W, calculations made with 17% of orbit in shadow.

7.3 Battery

Batteries are needed when the satellite is eclipsed. The storage should be sufficient for one worst case orbit plus a buffer. The solar cells give the same amount of charging every cycle. This charging might not always be as much as the used energy but the important thing is that the charging exceeds the used energy overall. Power budgets are used for calculating the needed battery storage.

Power calculations nCube -worst case

Orbit period [min]	96
Ground st. pass [min]	11
Remaining [min]	85

			Peak power			Sleep-mode				Power
		Voltage			Time			Time	DC/DC	consume
Subsystem	**Description**		**mA**	**mW**	**min**	**mA**	**mW**	**min**	**eff.**	**[mWorbit]**
VHF receiver	**TBD**	3,3	100	330	96	50	165	0	90 %	329,1
TNC	16LC77 microcontroller	3,3	4	13,2	96	0	0	0	90 %	14,5
Telecommand unit	Atmel Atmega32L	3,3	2	6,6	96	0	0	0	90 %	7,3
UHF transmitter	**TBD**	4	430	1720	11	0	0	85	90 %	216,8
S-band transmitter	Andøya Rocket range	5,5	300	1650	11	0	0	85	80 %	226,9
ADCS magnetometer	Honeywell HMC2003	6,5	20	130	96	0	0	0	80 %	156,0
ADCS magnet coils	100 turn, 0.0075 m^2	6,5	25	163	96	0	0	0	80 %	195,0
ADCS OBDH	**TBD**	3,3	2	6,6	96	0	0	0	90 %	7,3
AIS receiver	**TBD**	3,3	50	165	96	0	0	0	90 %	181,5
AIS OBDH	Atmel Atmega128L	3,3	2	6,6	96	0	0	0	90 %	7,3
Onboard system clock	Dallas DS130S	3,3	0,1	0,33	96	0	0	0	90 %	0,4
Power management unit	16F442 microcontroller	3,3	2	6,6	96	0	0	0	90 %	7,3
In house sensors	Volt, temperature, mA	3,3	0,5	1,65	96	0	0	0	90 %	1,8
								Total energy		**1351,0**

Consumption	**1351,0**	**[mWorbit]**
Payload turned off	**793,9**	**[mWorbit]**
From solar cells	**942,81**	**[mWorbit]**

Figure 59: Power calculations of nCube. Worst case consumption and energy from solar cells displayed.

The power budget gives a picture of worst case scenario. This will probably not happen that often. The consumption is higher then the charging. In normal operation the consumption is about 990mWorbit, not 1351mWorbit which is worst case. This will give an energy shortage of about 50mWorbit. In worst case consumption there will be a power shortage of about 400mWorbit. The energy from the solar cells will more likely to be about 1200mWorbit. If looked only on the power calculations, a small battery would be sufficient. When the satellite leaves the POD and starts the operation, it will consume much energy. It needs to be stabilized; the ADSC will use much energy. The tracking of the satellite will also use much energy in the beginning. This implicates the use of a bigger battery. The batteries used on the satellite are Danionics 485368, 1500mAh. Two batteries are used in parallel giving a total capacity of 3000mAh at 4.2-3.7V. The batteries are allowed to be discharged 70%. The available energy are 3000*3.7*0.7=7770mWh. This gives a maximum discharging for one orbit; 7770/96*60=4856.25mWorbit.

Battery	Cell voltage [V]	Capacity [mAh]	Max dich.	Capacity [mWorbit]
Lithium Ion (2 in parallel)	3,7	3000	70 %	**4856,25**

Figure 60: Battery capacity

Several batteries have been tested. The charging cycle consist of charging the battery with a constant current, max 0.7 CmA (1.0 CmA means the total battery capacity), until the voltage reaches 4.2 Volt. Then the voltage will be constant until the current drops to 0.07 CmA. If the battery voltage is below 2.9 Volt the charging current shouldn’t be higher than 0.1 CmA. In the satellite the power management system won’t let the battery voltage drop as low as 2.9 volt. Because of this we don’t need to construct such a charger.

Two different types of batteries have been tested, one 1800mAh battery from Gylling and one 1350mAh battery from Danionics. The discharging of the Gylling battery was done by a constant current at 1 CmA until the battery voltage was 3.0 Volt. By measuring the voltage, information about how that battery behaves was gathered. The battery from Gylling was mistreated by charging it with reversed polarity for a few seconds. This treatment made the battery lose about 90% of its capacity.
The Danionics battery has been tested in a vacuum chamber. The battery was slightly deformed and needs to be placed in some kind of box to handle the vacuum in space.
The Danionics battery was a Li-ion polymer battery with extended temperature range. This batter is tested in different environments and loads. The battery used on the satellite is the same type as the tested one but with a bigger capacity; 1500 instead of 1350mAh.

The efficiency between charging and discharging is over 95%. With extreme low temperature the battery voltage falls approximately 0.7 volts.

Danionics battery data DLP455660:

Max discharging current 1350mA
Max charging current 950mA
Max charging voltage 4.2 V
Min discharging voltage 3.0 V
Battery fully charged at 4.2 volt and 90mA

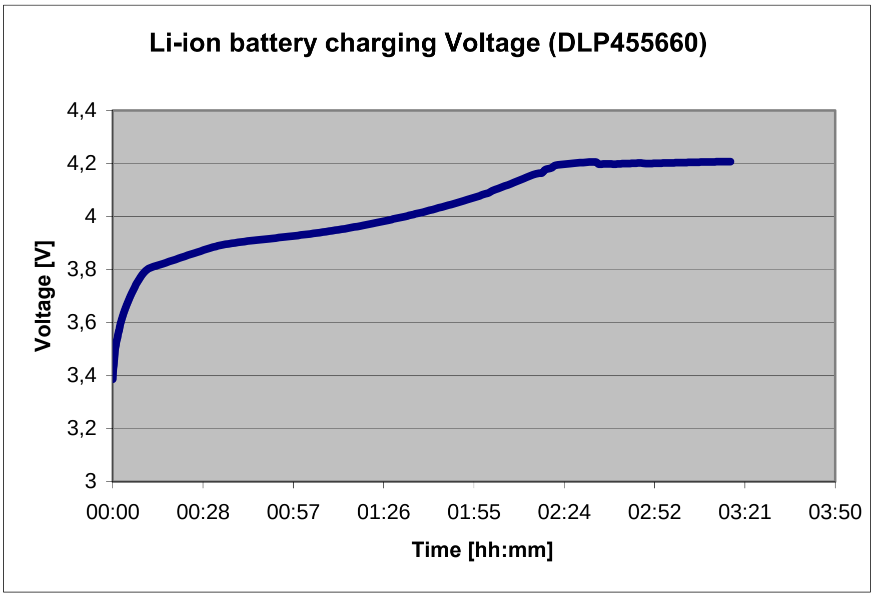


Figure 61: Shows the voltage characteristics when charging a 1350mAh Li-ion battery at 22°C. Charging with a constant current until the battery reaches 4.2V.

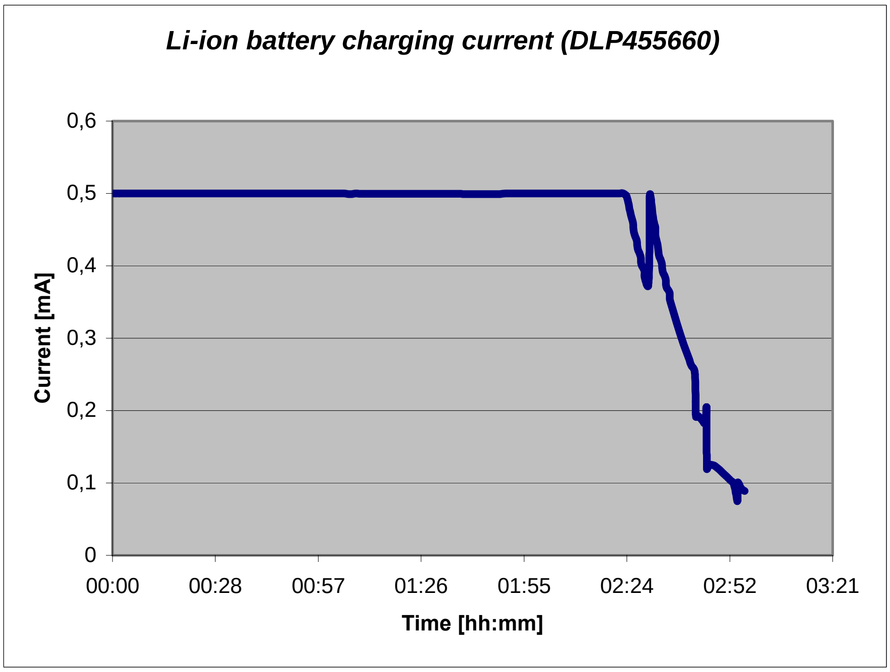


Figure 62: Shows a constant charging current (500mA) when charging a 1350mAh Li-ion battery at 22°C until the current drops when the battery reaches 4.2V.

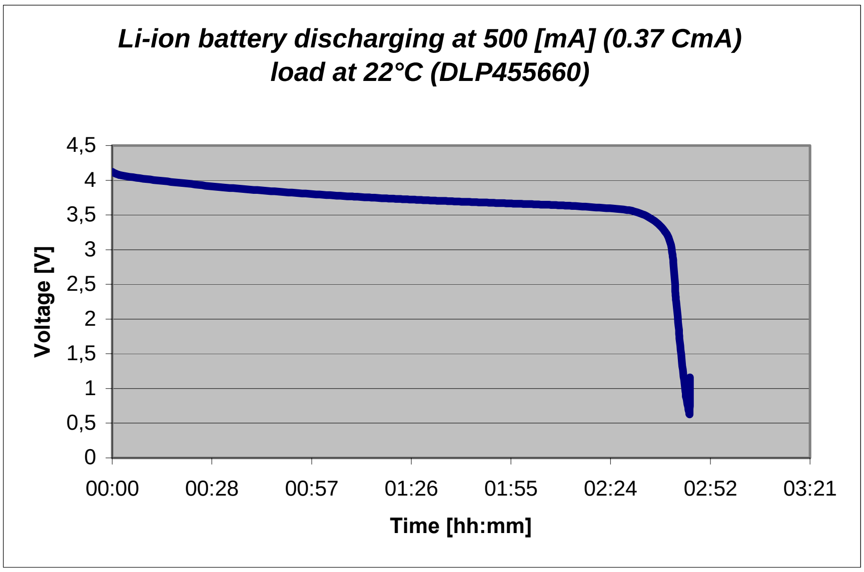


Figure 63: Shows the discharging characteristic of a 1350mAh li-ion battery, with a constant 500mA load at 22°C.

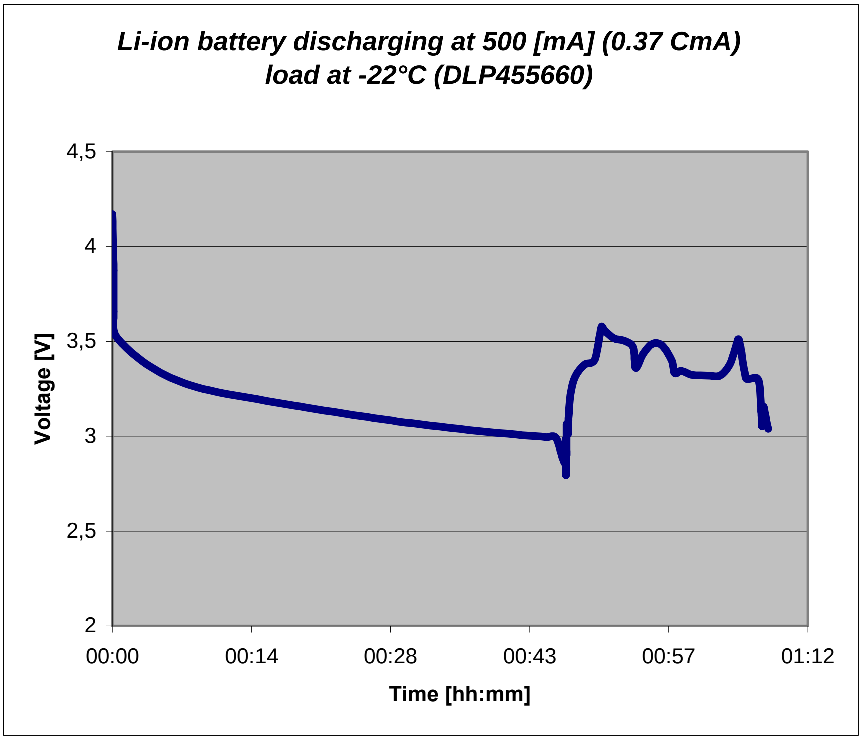


Figure 64: Shows the voltage level at -22°C for 47min (down to 2.9V), then heated up to + 22°C for the rest of the time. Constant 500mA load.

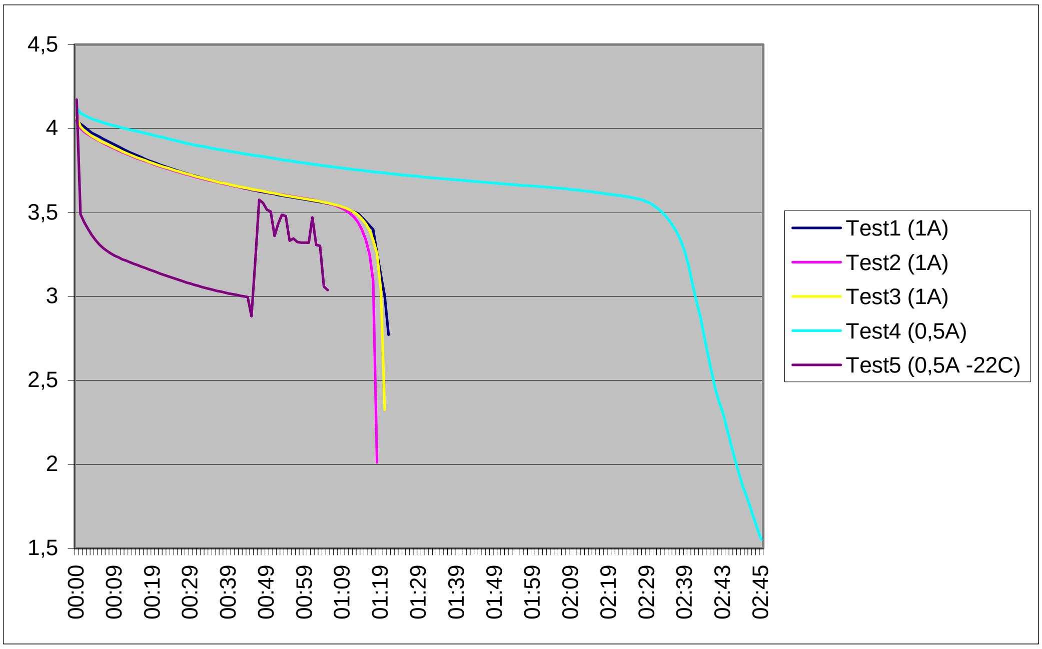


Figure 65: Shows a comparison of the different discharging experiments on the Li-ion battery (DLP455660).

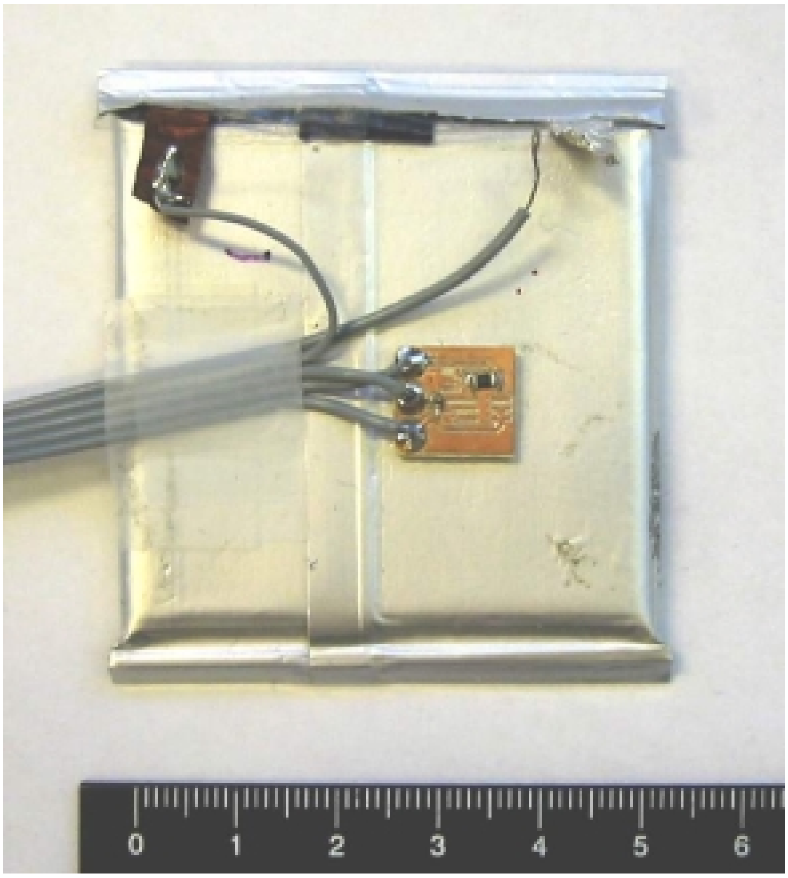


Figure 66: Picture of the Danionics 485368 1500mA Li-Ion battery and a temperature sensor.

7.4 Antenna release

The antennas are supposed to be launched with a certain time delay after satellite leaving the POD. This is a demand for using the launch POD. This system must be as fail safe as possible; without the antennas in position communication cannot be established. To avoid that the time delay system is depending on any other system (PMU f ex) a separate system is constructed. The release system glows a nicrome wire that burns of a fishing wire. The broken fishing wire releases the antenna.

This system is based on the 555 circuit. When the satellite leaves the POD and the kill-switch turns on, the voltage rises to approx 4.2V on the unregulated power-bus. This unregulated voltage is connected to the release system. The 555 circuit is a RC timer capable of generating accurate frequencies and time delays. In this application the circuit is used as a one shot. When the 555 gets power (unregulated power bus) on the V+ pin the counter starts to count and after a certain time the output goes from high to low. The output will continue to be low forever. The actual time delay on the antenna release isn't set yet but will most likely to be 30s-1min. The 555 is used together with an N-channel MOSFET transistor. The MOSFET opens when the gate turns low. The output of the MOSFET is connected to the nicrome wire. It is critical that not only the fishing wire but also the nicrome wire. This will prevent the battery from being completely drained. To make sure that the nicrome burns off, the wire has to be short. Tests have shown that the wire can not exceed ~1.5cm. This is due to the high resistance in the wire.

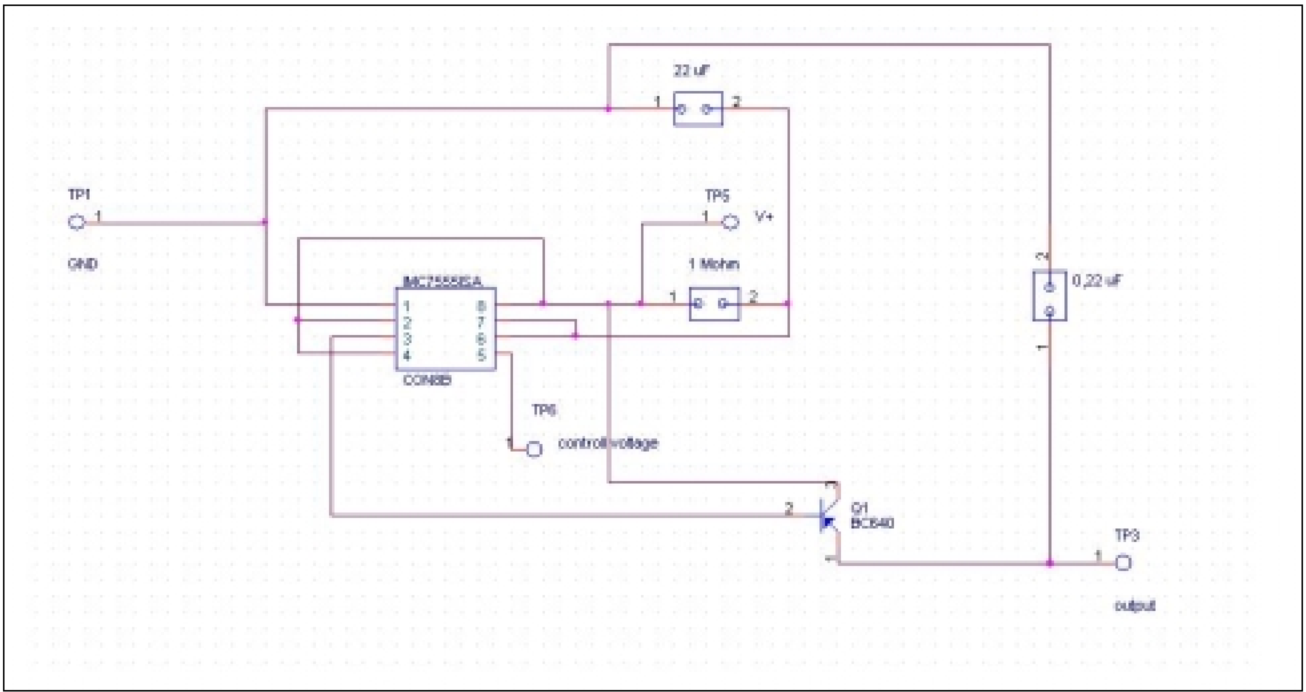


Figure 67: The antenna release circuit, a 555 timer and a N-channel MOSFET.

The delay time is depending of a resistance and a capacitance.

$T_{output} = 1.1 * R*C$

In our case R = 1Mohm and C = 22uF making T_{output} to 1.1*1M*22u = 24.2s, this is the time delay.
The 0.22uF filter capacitance is used to prevent the nicrome from gluing at time t = 0. This could cause the satellite to get wedged in the POD. There is always ripple on the output when the circuit is powered up. The filter capacitance is damping that.

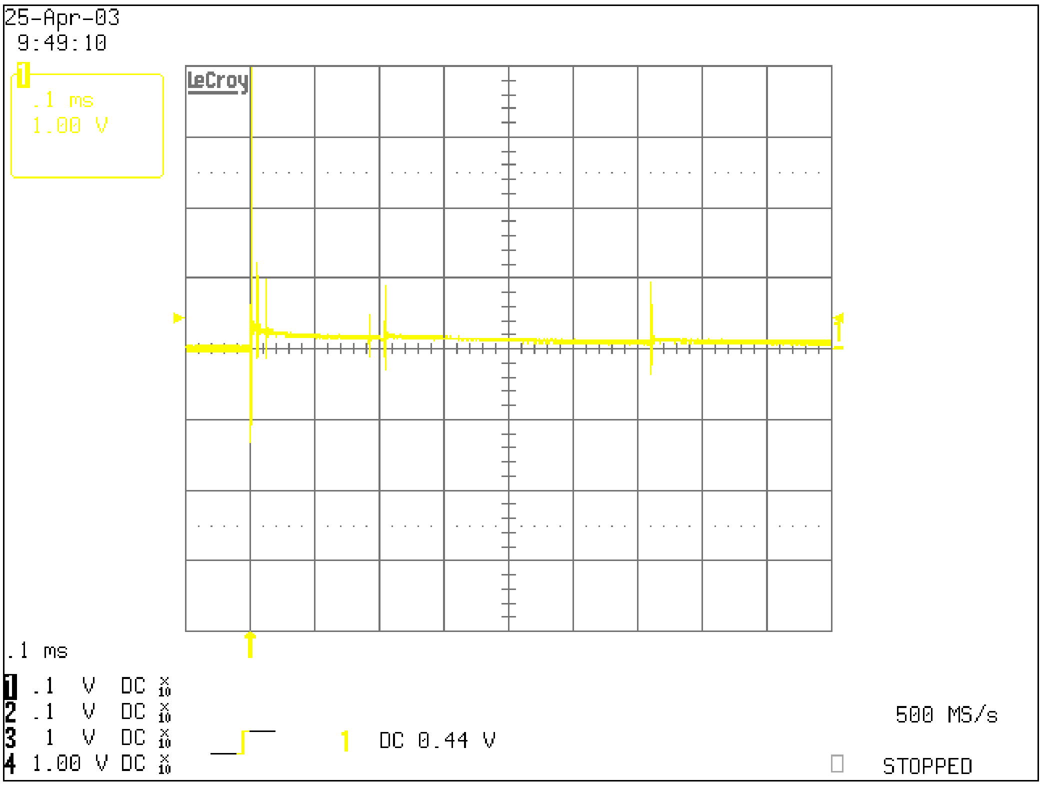


Figure 68: Output voltage at time t = 0 without 0.22uF filter capacitance. Ripple could accidentally glow the nicrome wire.

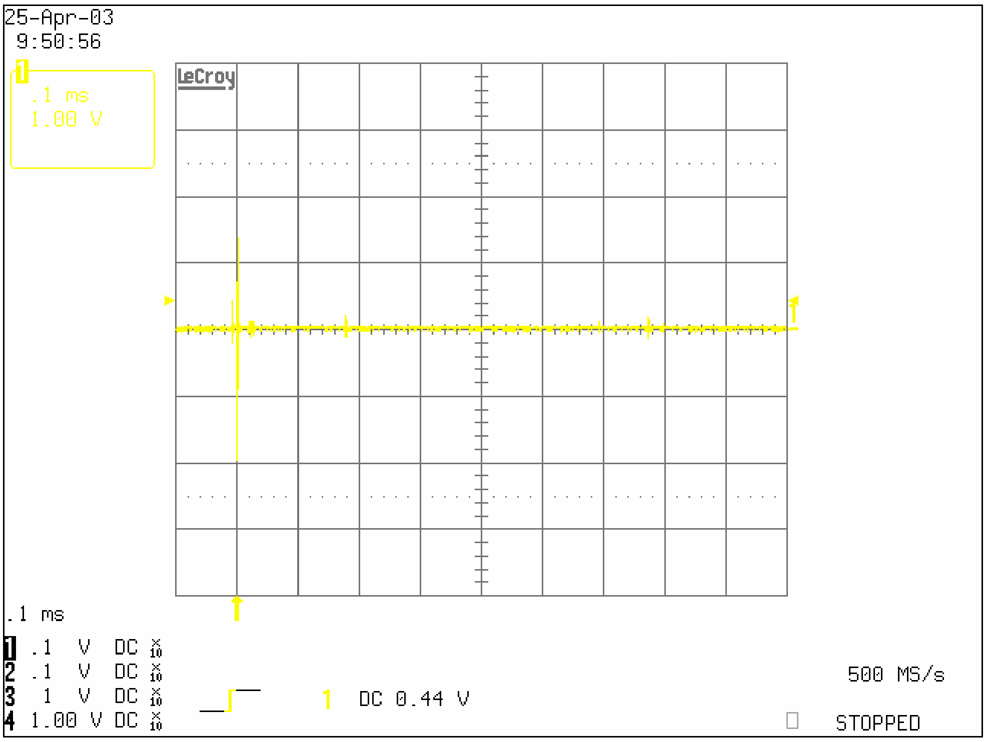


Figure 69: Output voltage at time t = 0 with a 0.22uF filter capacitance. Ripple is reduced and the possibility that the nicrome will glow at t = 0 is gone.

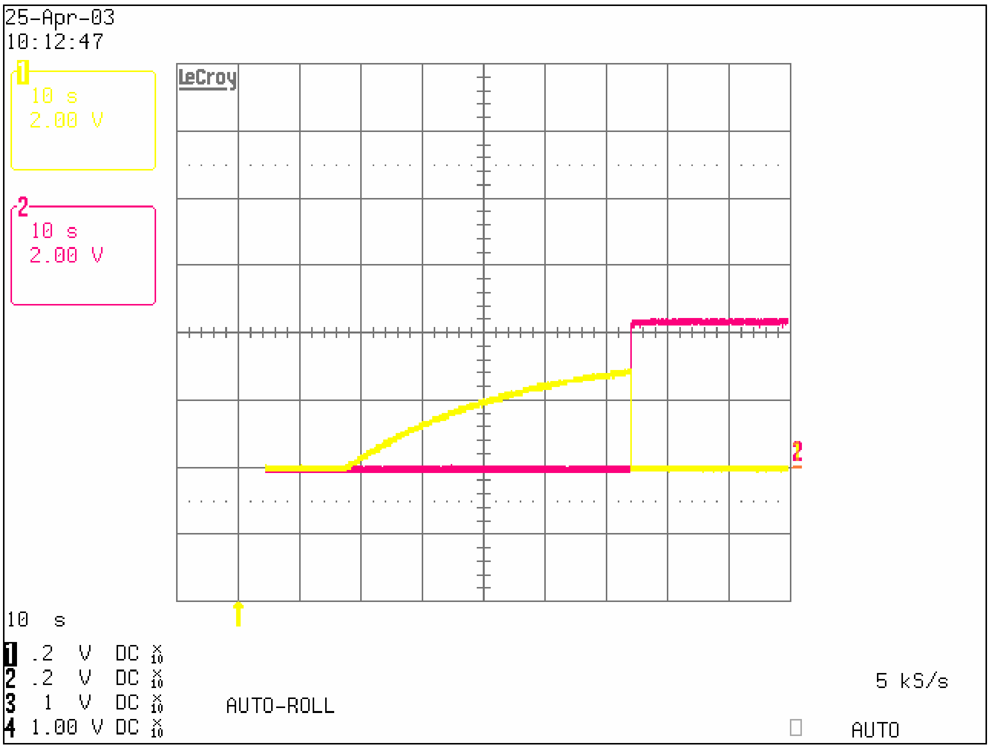


Figure 70: Channel 1 shows voltage building up at 22uF capacitance. When the voltage reaches 2/3 of V+ the 555´s output pin goes low. Channel 2 shows output from MOSFET.

One problem with the circuit is that the calculated delay time seems to be much shorter than the time in the tests performed. In the tests the time was ~45s instead of the calculated 24s.

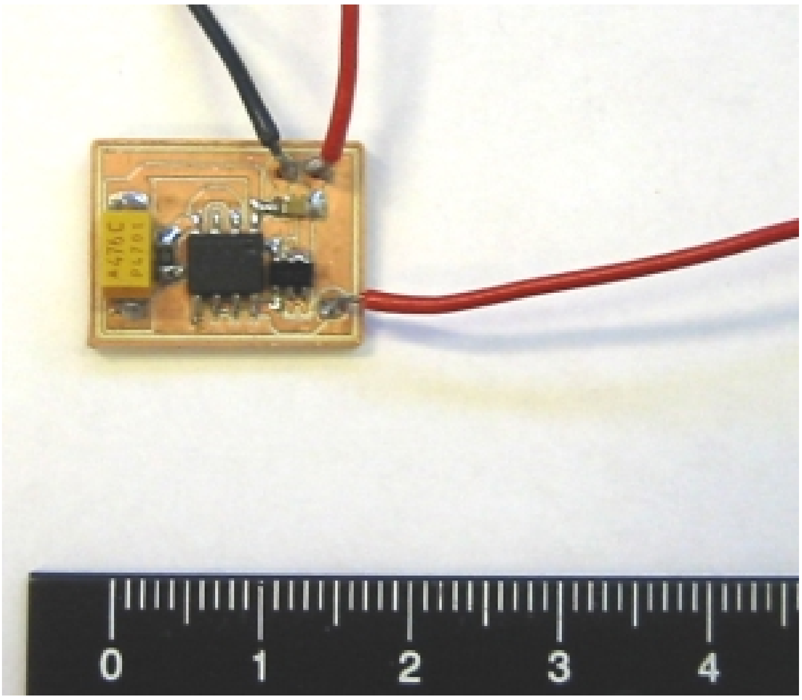


Figure 71: The actual antenna release circuit. Size in centimeters.

7.5 Structure

In the nCube satellite project there are many participants and therefore god communication and documentation is of a high priority. After the prototype implementation in Trondheim march 2003 some demands on size and placement of the PCB in the structure where made. To be able to make the system fit, the Power Group (us) made a drawing of the structure showing where to connect the different PCB to the backplane, and mounting the power PCB / backplane to the structure. All the different measurements are documented in these drawings.

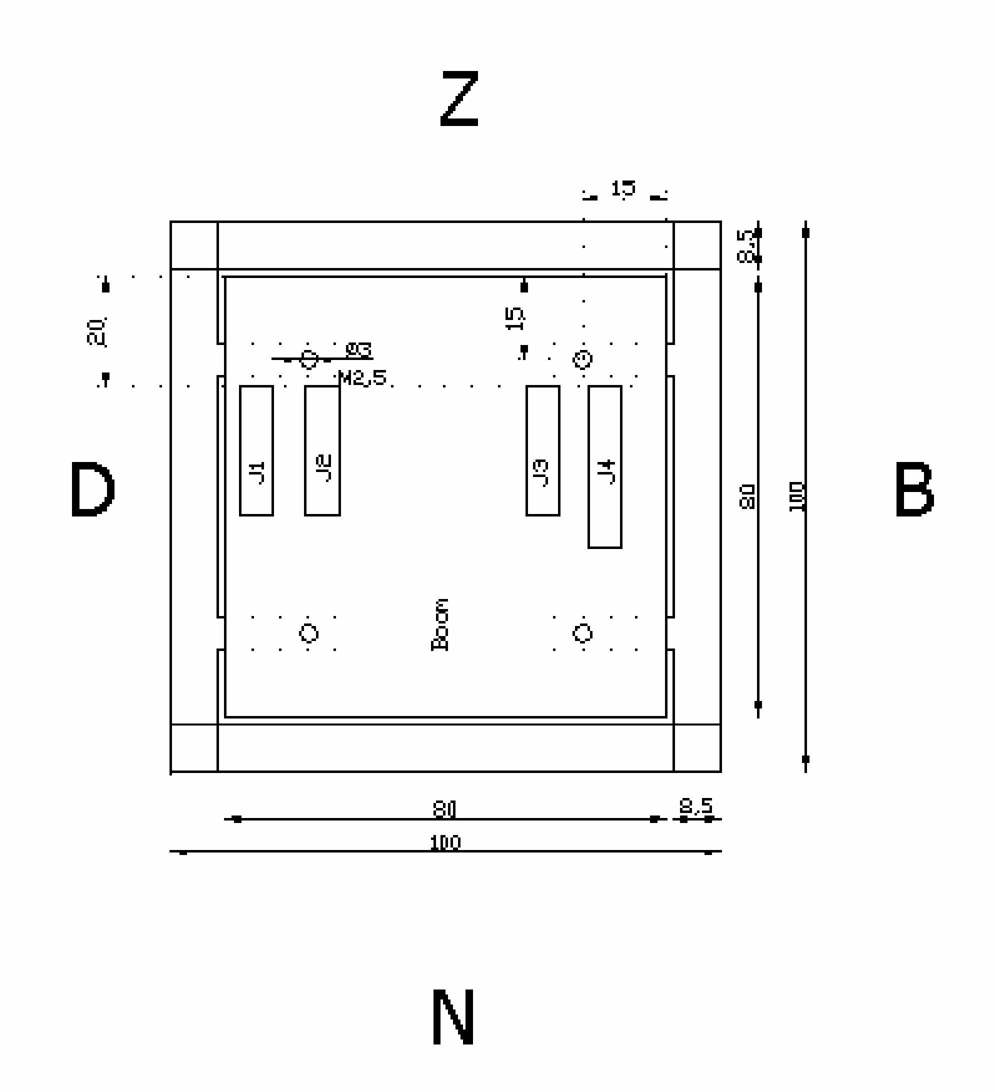


Figure 72: The backplane when locking in through the A side of the structure. All the measurements is in millimeters.

The picture shown above is a picture of the structure when locking through the A side of the satellite. J1 – J4 is the connector to the subsystems. The small circles are spacing to put a M2.5 screw when attaching the backplane which measure 80*80 mm to the structure. The space between J2 and J3 is where the gravity boom and batteries are placed. This picture mainly shows the outer measurements on the satellite.

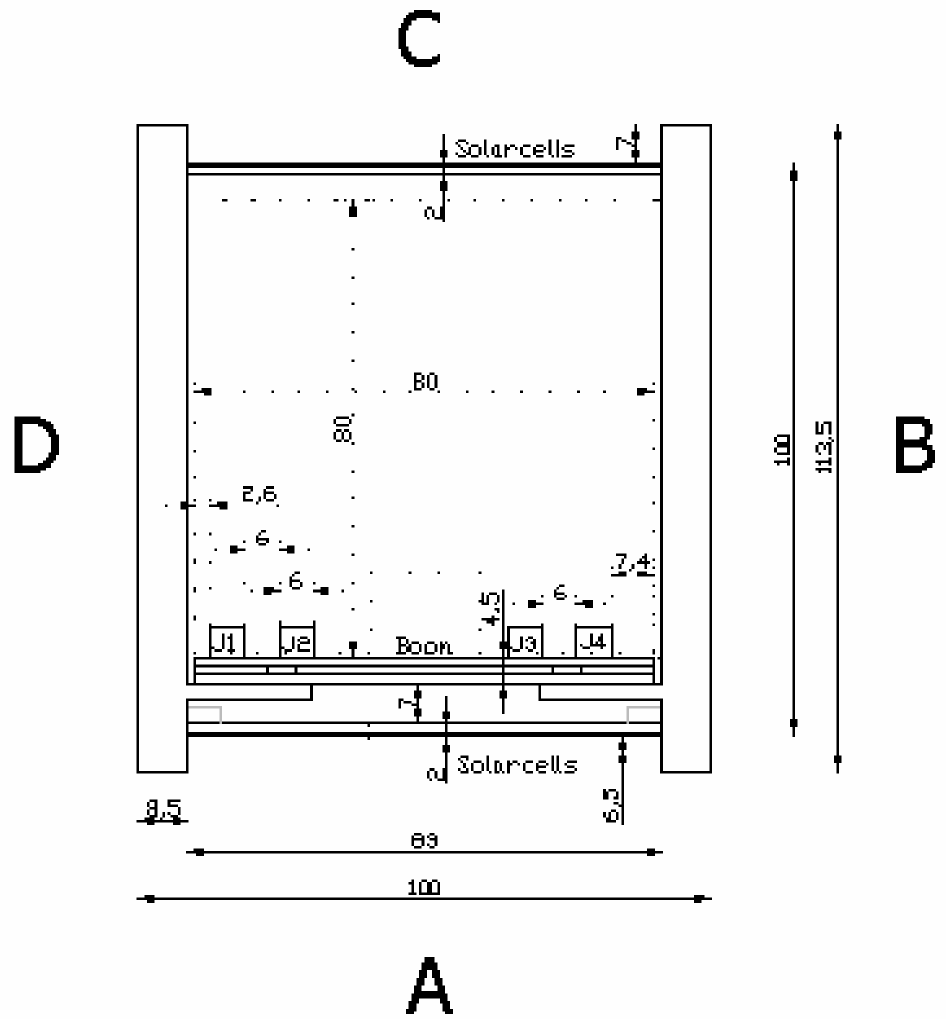


Figure 73: The jumpers when locking in to the satellite through the Zenith side. All the measurements is in millimeters.

The picture above shows the structure when locking through the Zenith side of the satellite. This picture gives a more detailed description on how much space each subsystems PCB has available. The PCB should be placed on the right side of the jumper with all the largest components over the jumper or on the left side of the PCB.

7.6 The backplane/power PCB

The backplane has two mayor tasks. The different subsystems need to be connected to each other and to the power management system. The backplane handles these things. The backplane is also a part of the structure, stabilizing the subsystem PCB´s. It consists of two double-layer PCB´s forming a sandwich structure. The top PCB (backplane) has the connectors to the subsystems and the power management unit (PMU). The bottom PCB (power PCB) has the DC/DC converters and a ground plane.

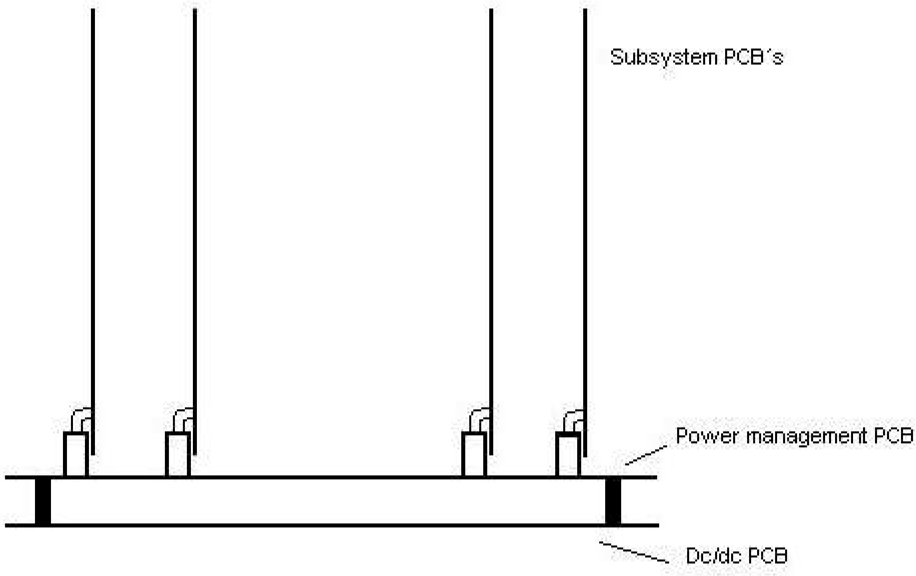


Figure 74: Schematic picture of the satellites PCB´s.

The dc-dc converters are placed at the bottom, the ground plan is shielding the top PCB from the high frequent switching of the dc-dc converters. Nearly all IC´s are places on top of the top PCB. This is done to make them less vulnerable of EMI created by the DC/DC´s. The PCB´s are connected to each others by a series of long vias. The cards are separated from each other by four 3mm washes. The PCB used is a standard 1.6mm epoxy board. This will be stiff enough for supporting the subsystems thru the connectors.

7.6.1 The backplane PCB

The power management board has a series of components; they are listed and described below. The traces on the PCB are made with a width of 0.4mm.

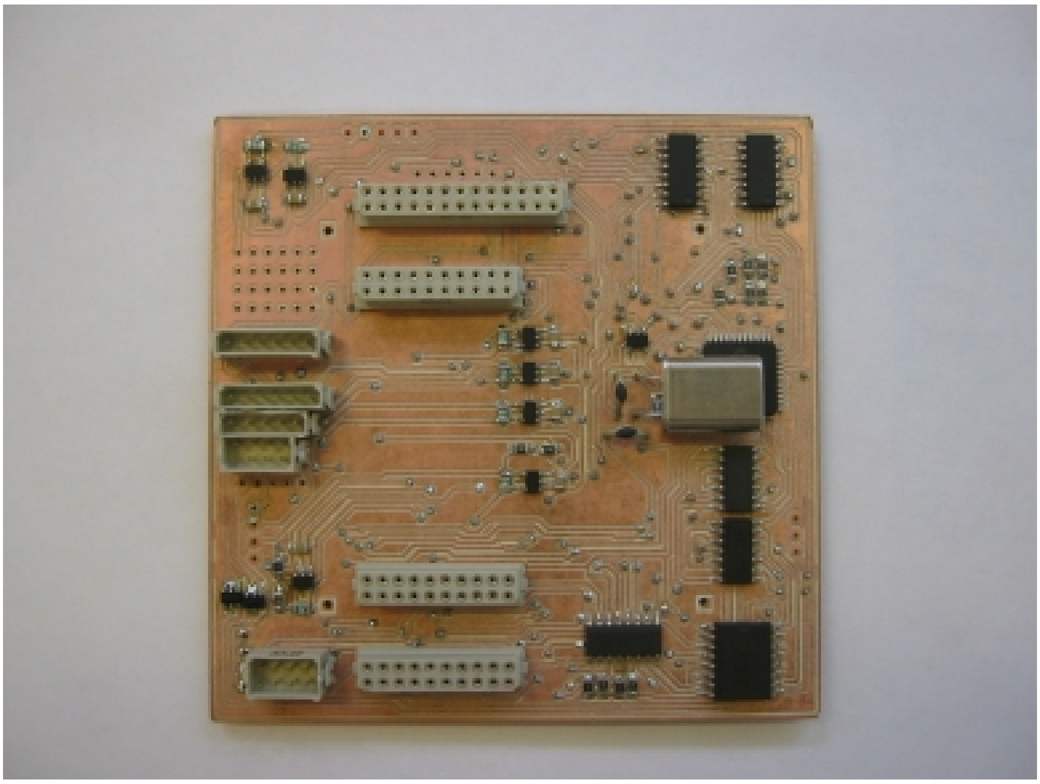


Figure 75: The top side of the power management board. All connectors and most of the IC´s are placed on this side.

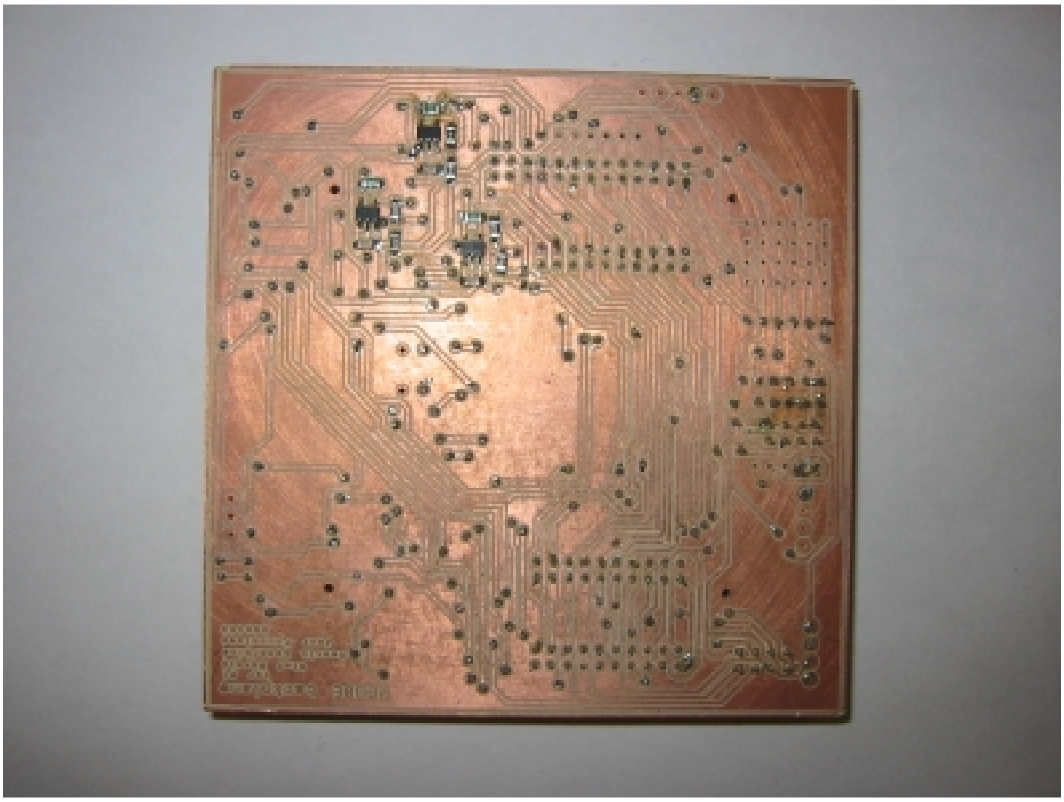


Figure 76: Bottom side of the power management board. This side has some IC´s and routing.

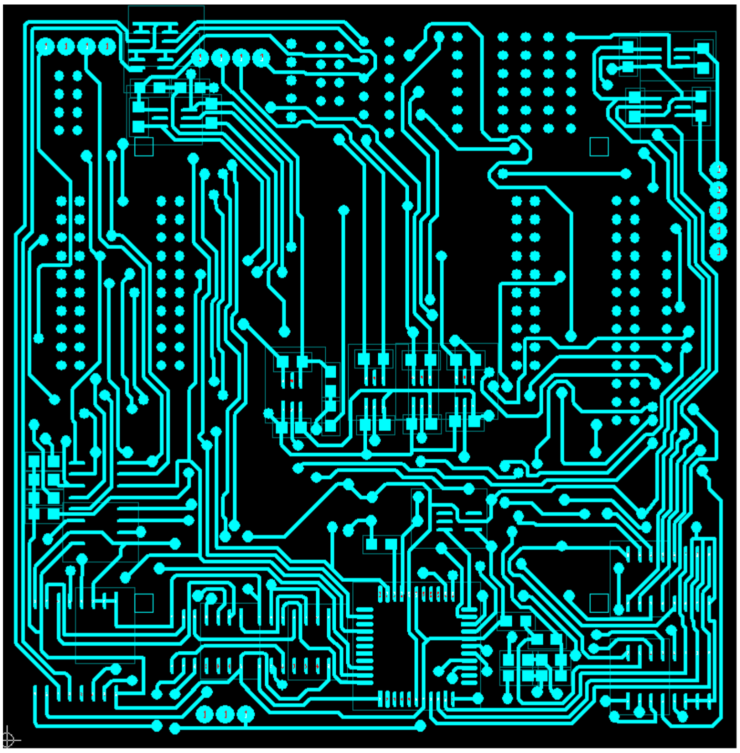


Figure 77: Layout of power management board. Top side.

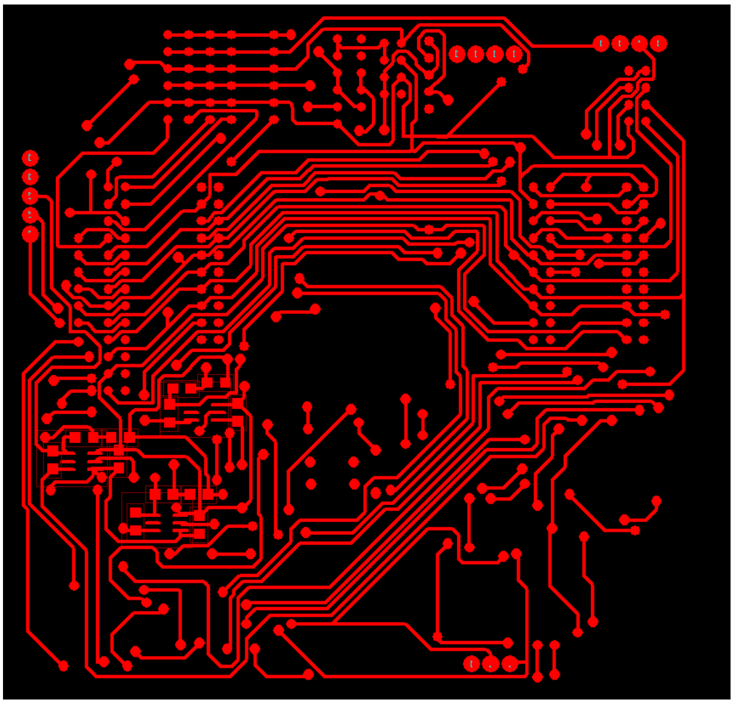


Figure 78: Layout of power management board. Bottom side.

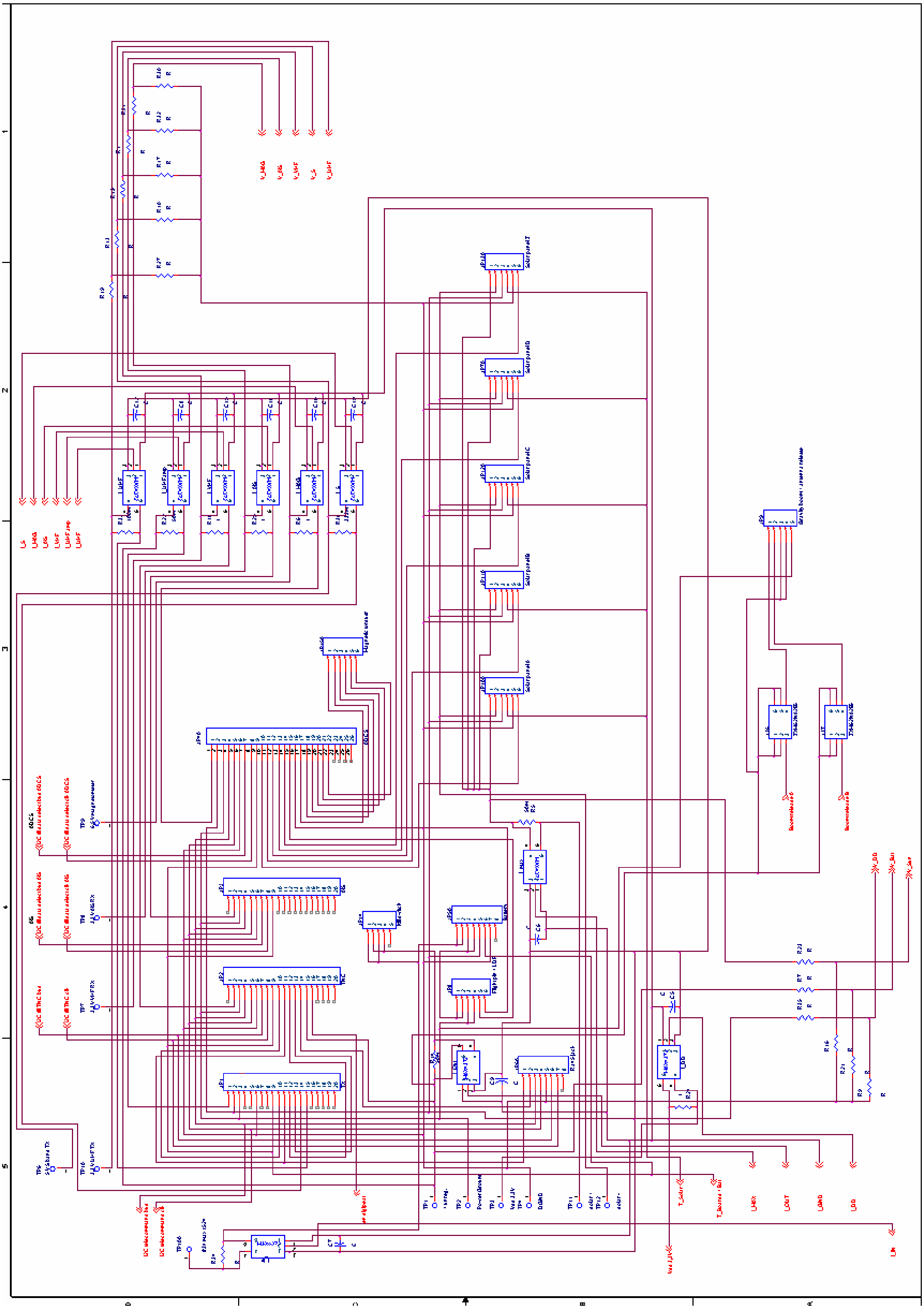


Figure 79: Circuit layout power management PCB.

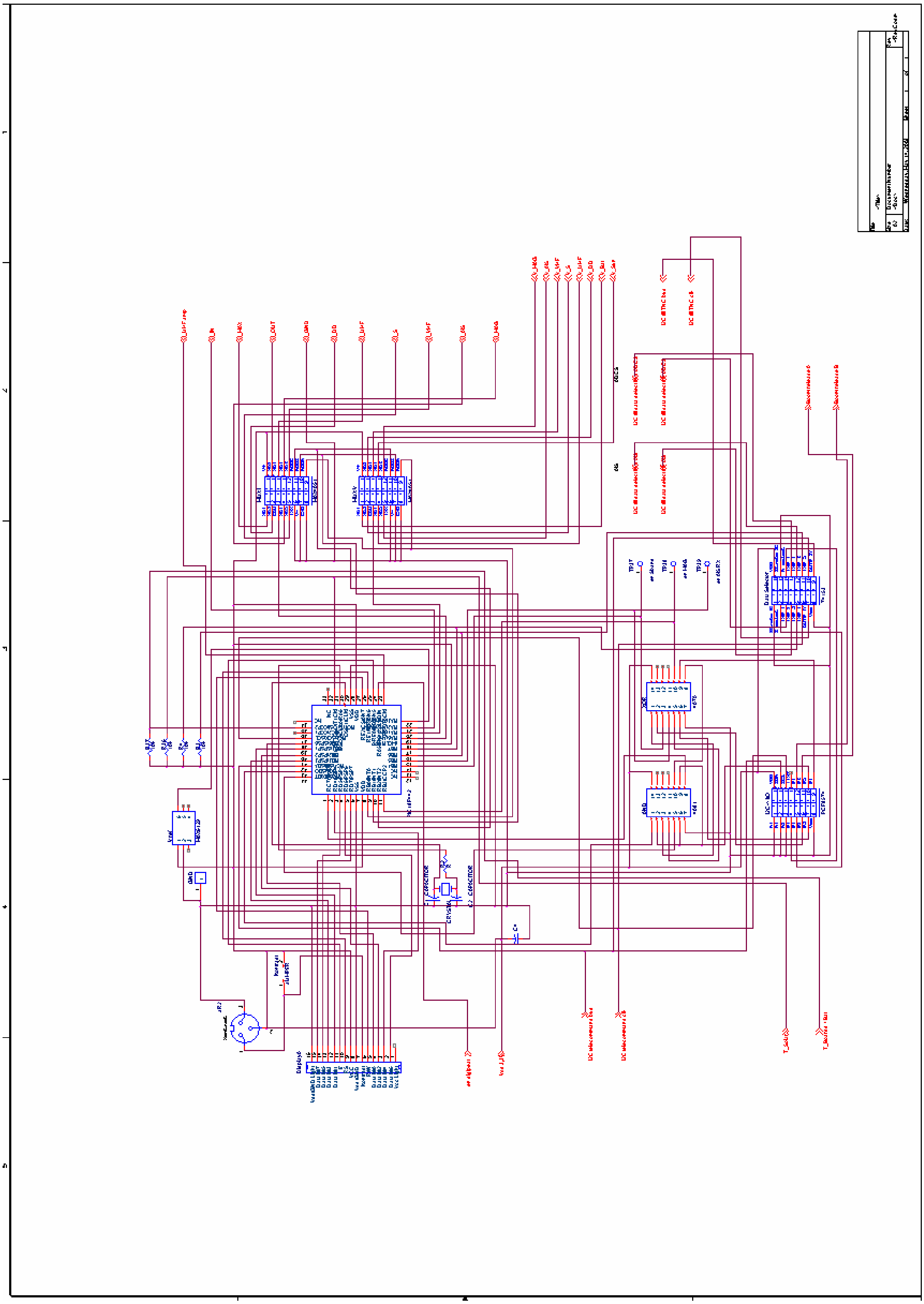


Figure 80: Circuit layout power management PCB.

7.6.1.1 The microcontroller

The processor that has been chosen is a PIC18LF452 microcontroller from Microchip. This is a 44 pin CMOS FLASH-based 8-bit microcontroller. It has 34 I/O pins and has eight 12 bits A/D channels. Each I/O can be set to be eider an input or output. This can also be changed when the program is running. It has also a built in hardware I2C bus interface, which is used to communicate with TNC. The processor also has a lot of other features that has not been used.

The processor is guarantied to run with a 40MHz processor crystal, which makes 10 MIPS. But to save power and to make it more reliable it runs with a 2MHz crystal.
The processor has a 32Kbyte FLASH program memory, 1536 byte RAM and 256byte EEPROM.

The power management program uses about 3Kbyte program memory, 256 byte RAM and 4 byte EEPROM, so there is a lot of memory left.
The processor is programmed in MPLAB using Assembly code.

7.6.1.2 The sensors

There are tree types of sensors used in the power management and housekeeping system: temperature, current and voltage sensors. The data from the sensors are collected by the power management microcontroller (PMU), evaluated and then sent to earth. The temperature sensor uses digital interface, the voltage and current sensors uses analog. The microcontroller has a built in A/D converter, this is connected to a built in eight channel analog multiplexer; these channels are used for the analog interface.

7.6.1.2.1 Temperature

For this purpose a MAX6575 temperature sensor is chosen. This is a very simple sensor that takes small place and uses a 1 wire communication.
Temperatures are sensed by measuring the time delay between the falling edge of the triggering pulse from the processor and the falling edge of the sensors response signal. Different sensors on the same I/O line use different time multipliers to avoid overlapping signals.

The sensors have eight different time multipliers; these are selectable by using the two select pins on each device and choosing the "L" or "H" version. The "L" version provides four delays ranges less than 50ms. The "H" version provides four delay ranges greater than 50ms.

In the satellite there are 11 sensors connected to two different communication busses. There are two different ways to measure the temperature from the sensors, by measure the time between the trig pulse and the falling edge of the sensors response signal, or by measure the time of the response signal. The response signal multiple is the same for all the MAX6575 sensors.

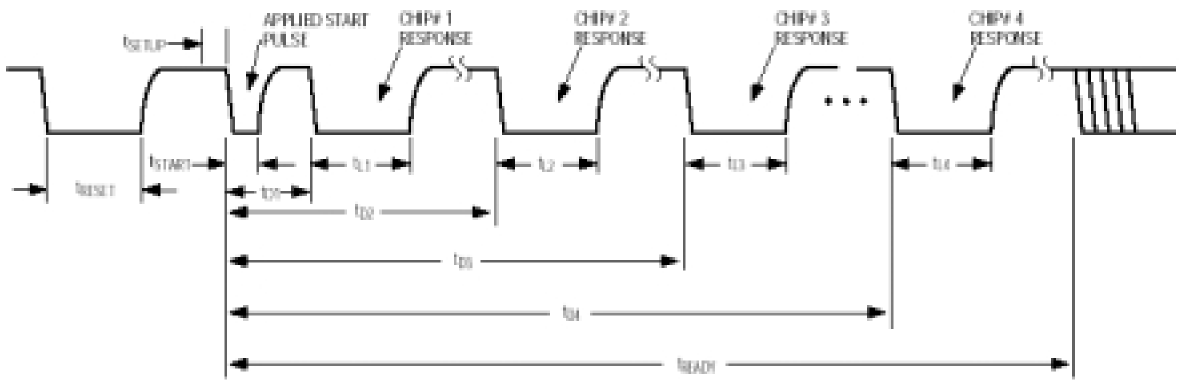


Figure 81: Response times of the different temperature sensors.

The length of the response signal is easiest to use, because than all sensors have same time-to temperature scale, and therefore this has been used. Because it isn't possible to connect more than 8 sensors to each bus, there are two different busses for measuring temperature. All the solar cell temperature sensors are connected to one bus, and the subsystems and batteries is connected to the other one.

To read all the temperatures the processor reads one bus at the time, first the batteries/ subsystems and then the solar cells. The program is made to first resets all the sensors by pulling the buss low for a specified time. Then the trig pulse is sent out, and a timer is started. When the sensor pulls the bus low (response signal) another timer is started, this timer runs until the bus is driven high again. This time on the second timer is proportional to the temperature:

The first timer is restarted in every rising response flank; this timer is used to detect malfunctions in the sensors, if one of the sensors doesn't response in its time zone, an interrupt occurs. When that occurs, an error code is saved instead of the temperature.

7.6.1.2.2 Current

The current sensor used is the MAX4372. It is a small current sensor which has an analog output depending on the current. The sensor measures the voltage fall over a resistance R_{sense}. R_{sense}´s value is calculated by: max V_{out}/Gain/max I_{sense}= R_{sense}. The gain is 20. An A/D converter is used to convert the analog output to a digital number. The microcontroller has a built-in A/D converter handles this task. Because of the number of current sensors exceed the available converter channels; an external analog multiplexer (MUX) is used. The MUX is addressed by the microcontroller that receives the selected sensor value.

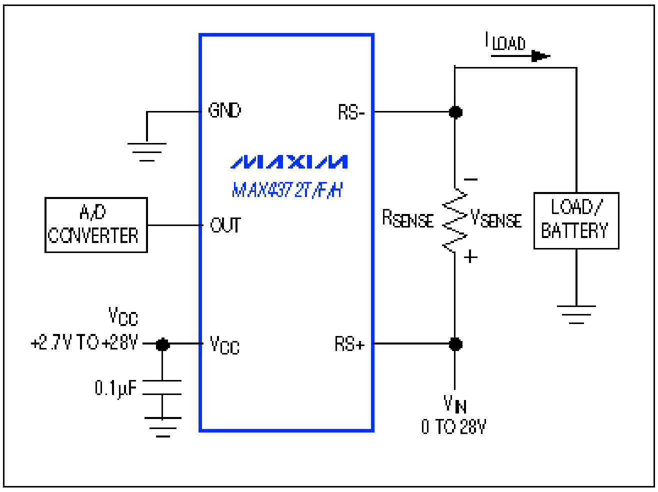


Figure 82: The MAX4372 current sensor circuit.

Current	**R_{sense}**	
I_MAX	50	mΩ
I_OUT	50	mΩ
I_S	100	mΩ
I_MAG	1	Ω
I_AIS	1	Ω
I_UHF	1	Ω
I_VHF	100	mΩ
I_DD	1	Ω
I_IN	50	mΩ
I_UHFAMP	50	mΩ

Figure 83: Chosen R_{sense}.

7.6.1.2.3 Voltage

There is no need for a sensor to measure the voltage. The point where the voltage is measured is connected directly to an A/D converter. The output is a digital number that is dependent of the voltage. The microcontroller has a voltage reference set to 2.5V. The A/D converters measure the voltage between 0 and the reference. To be able to measure voltages that are higher then V_{ref} voltage dividers are used. R1 is connected between V_{sense} and $V_{A/D}$. R2 is connected between $V_{A/D}$ and ground.

Measured voltage	R1	R2
V_DD	100kΩ	100kΩ
V_BAT	100kΩ	100kΩ
V_SUN	100kΩ	100kΩ
V_MAG	150kΩ	50kΩ
V_AIS	100kΩ	100kΩ
V_VHF	100kΩ	100kΩ
V_S	150kΩ	50kΩ
V_UHF	100kΩ	100kΩ

Figure 84: The resistances used in the voltage cutters for the voltage sensors.

The microcontroller has only a limited number of A/D converter channels; that is why a external MUX is used for the voltages as well as for the currents. The microcontroller addresses the MUX to receive the selected value.

7.6.1.3 The multiplexers

Because of the limited number of A/D converter channels on the microcontroller, external multiplexers are used. The one used is an analog type, MAX405. The MUX must be able to handle analog values because it shall be connected to the analog sensors. The MUX has eight inputs and one output. The microcontroller addresses the MUX and receives the selected value. There are tree address pins to address the eight inputs. There are two multiplexers used on the satellite, one to handle the current sensor values and one to handle the voltages.

I MUX	
Address	**Sensor**
0	I_MAG
1	I_MAX
2	I_OUT
3	I_DD
4	I_UHF
5	I_S
6	I_VHF
7	I_AIS

Figure 85: The addresses of the current sensor MUX.

The I_IN and I_UHFAMP sensors are connected directly to the microcontroller.

U MUX	
Address	**Sensor**
0	V_SUN
1	V_BAT
2	V_DD
3	V_S
4	V_VHF
5	V_AIS
6	V_MAG
7	V_UHF

Figure 86: The addresses of the voltage sensor MUX.

The enable system for the DC/DC converters

One of the tasks for the power management system is to turn of systems that fail. This is made to prevent that a failing system drains the batteries. This task can be override by the TNC, if the PMU (Power Management Unit) fails.
The systems that can be turned off are: the S-band transmitter, the magnetometers and the AIS receiver. There is some logic connected to the DC/DC converter enable pins. The logic used is a AND and a XOR gate. The AND gate (4082) is used for enabling the PMU control, the XOR (4070) for turning the subsystems on/off.

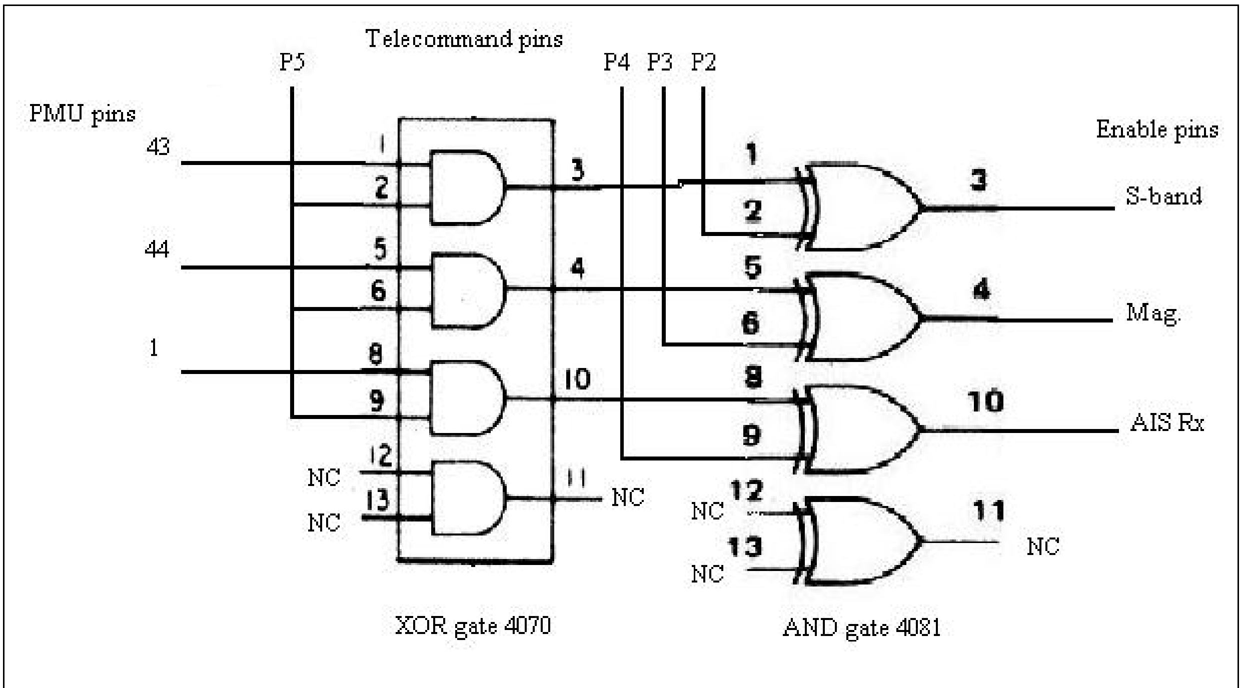


Figure 87: The logic gates used in the enable system.

The telecommand is the master of this system. If it turns PMU_enable low, the PMU is disabled from turning subsystems on/off.

7.6.1.4 The I/O expander

[16]

To be able to decode telecommands and to turn systems on and off an I/O expander is used. This is a device that listens to the I2C telecommand bus and interprets the information. The expander decodes the I2C protocol and can set a number of digital outputs. The expander used is a PCF8574 with 8 outputs. The expander is given a unique address that is used by the I2C protocol to address the expander. The bus protocol includes data of which pin that is supposed to be set. The I/O expander is a part of the communication system and the design is supplied by NTNU.

Output pin	Function
P0	Addresses the data selector.
P1	Addresses the data selector.
P2	Turn on/off the S-band transmitter (overrides the PMU).
P3	Turn on/off the Magnetometers (overrides the PMU).
P4	Turn on/off the AIS receiver (overrides the PMU).
P5	PMU enable PIN. Enables the PMU to turn systems on/off.
P6	Gravity boom release D.
P7	Gravity boom release C.

Input pin	Function
SCL	I2C clock bus.
SDA	I2C data bus.

Figure 88: Pin layout of the I/O expander.

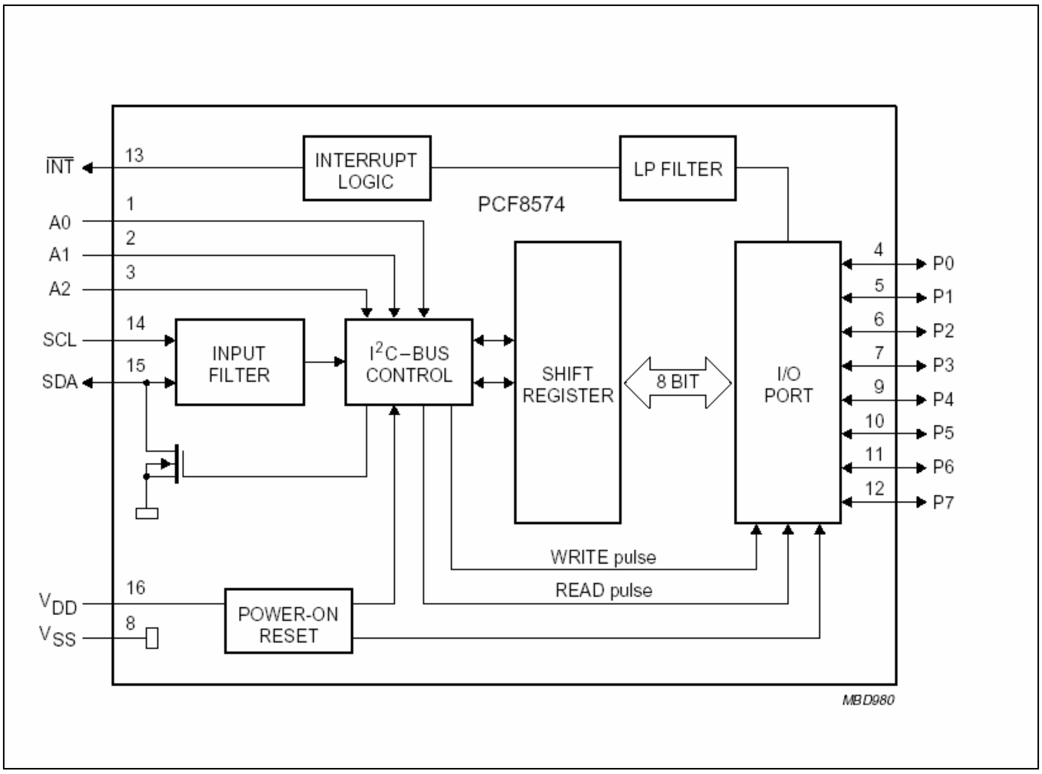


Figure 89: The PCF8574 I/O expander. The expander has address 000 for the I2C control.

7.6.1.5 The data selector

[16]

The data selector used (74153) has eight inputs and two outputs. The reason for using a data selector is to be able to choose from which subsystem, data shall be send to earth. Every subsystem has an I2C bus connected to the data selector. The data selector is addressed by the I/O expander who (by the telecommands) decides which I2C bus to connect to the TNC. The selector has two channels, I2C data and I2C clock, with four inputs and one output each. The data selector is a part of the communication system and the design is supplied by NTNU.

Channel 1: I2C clock	
Pin	**Function**
1Y	Output to TNC downlink.
1C0	Input from Telecommand
1C1	Input from PMU
1C2	Input from AIS
1C3	Input from ADCS

Channel 2: I2C Data	
Pin	**Function**
2Y	Output to TNC downlink.
2C0	Input from Telecommand
2C1	Input from PMU
2C2	Input from AIS
2C3	Input from ADCS

Addressing pins	
A select	Connected to P0 on the I/O expander
B select	Connected to P1 on the I/O expander

Figure 90: Pin layout of the data selector.

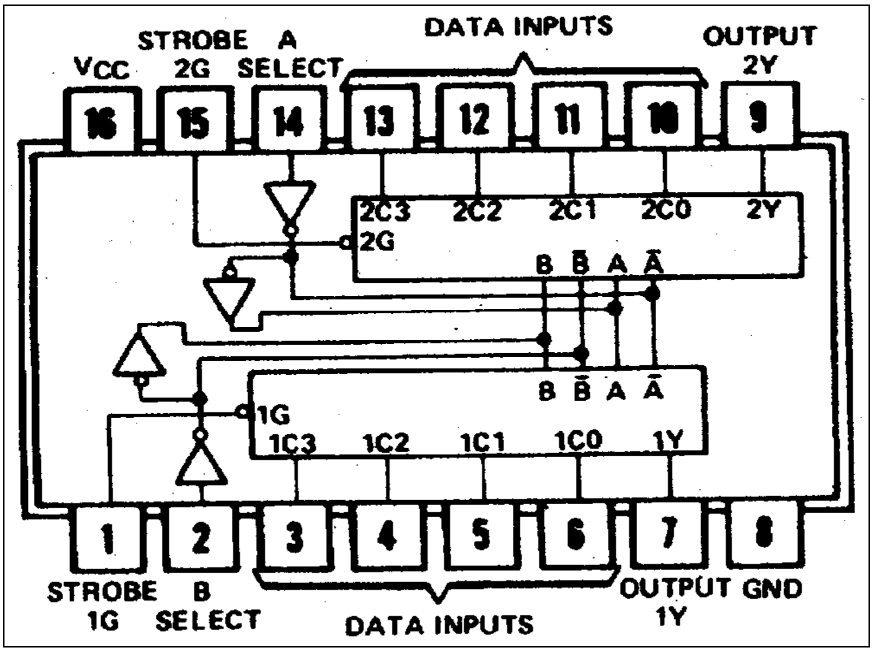


Figure 91: The 74153 data selector.

7.6.1.6 The subsystem connections

The backplane has a series of jumpers to connect the different subsystems of the satellite. There are four daughter boards connected to the backplane. The jumpers are placed on top of the power management PCB. All communication between the different daughter boards (subsystems) are done via the backplane. There aren't any other connections between the subsystems and the satellite. This will make it easier to assemble and test the satellite. The connectors used are Micronector200. This is a small connector with a pin offset of only 2mm. To use such a small connectors is a condition for the small backplane size. Even thou bigger connectors would create bigger stability to the structure, the available space on the backplane PCB set the limits.

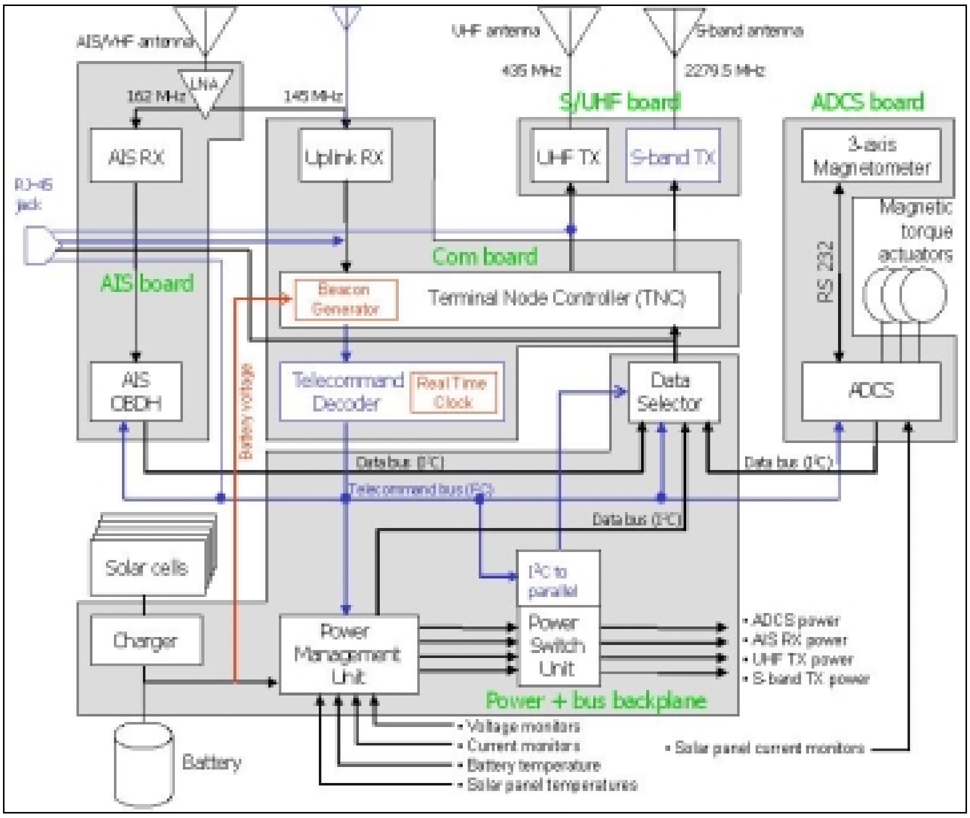


Figure 92: Structural picture of the satellite. The four subsystem boards (AIS, Com, S/UHF and ADCS) are highlighted in the top. Power and PMU board is in the bottom.

To save space on the backplane, some of the connections are soldered instead of using the Micronector200. The connections soldered are the ones who probably will stay in place after the first assemble. Such systems are; -the flight pin that is a part of the structure -all the solar cells except the one on the D-side.

7.6.1.7 Connectors

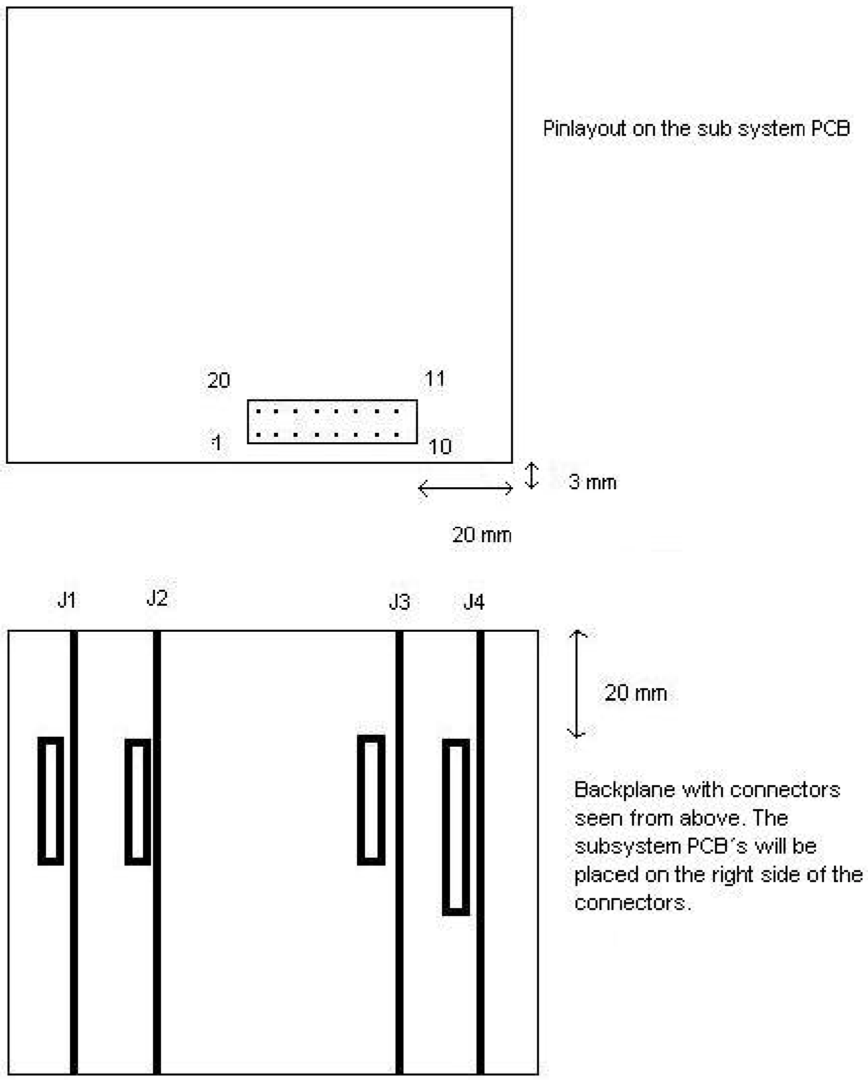


Figure 93: Pin layout of the connectors. The general layout on the PCB to place the Micronector200 is shown in the top picture.

7.6.1.7.1 Edge connector J1; UHF and S-band transmitter board

This is a female 20 pin edge connector. This board contains the transmitters. There are two transmitters on the satellite, the UHF and the S-band. The UHF sends at 435MHz and uses a ¼-wavelenght monopole antenna. The S-band sends at 2297.5MHz and uses a patch antenna.

Pin	Input/output	Name	Description
1	I	VccP	Battery voltage (3.3 - 4.2 V) for UHF power amplifier.
2	I	Vdd	3.3V for digital circuits. This voltage is not possible to turn off.
3	I	0	0 V (power ground).
4			NC
5			NC
6	O	DGND	Ground for digital circuits.
7			NC
8			NC
9	O	Temp	Temperature sensor bus.
10	I	TXs	S-band downlink data. Data to be sent to earth with the S-band transmitter. Using 9600 baud and the AX-25 protocol.
11	I	TXu	UHF downlink data. Data to be sent to earth with the UHF transmitter. Using 9600 baud and the AX-25 protocol.
12	I	TXS_en	S-band transmitter enable pin. This pin is used for enabling the transmitter and to start to transmit.
13	I	TXU_en	UHF transmitter enable pin. This pin is used for enabling the transmitter and to start to transmit.
14	I	VccS	5.5V for S-band transmitter. This Voltage is possible to turn off by the PMS.
15	I	VccS	3.3V for UHF transmitter. This voltage is not possible to turn off.
16			NC
17			NC
18			NC
19			NC
20			NC

7.6.1.7.2 Edge connector J2; VHF receiver and TNC board

This is a female 20 pin edge connector. The board contains the VHF receiver and the terminal node controller (TNC). The VHF receiver is the one that receives all commands from earth. It operates on 145MHz which is an amateur radio band. The VHF receiver is connected to a 400mm dipole antenna. The TNC is the controller for the up and down link. It makes sure that the transmissions up and down doesn't disturb each others. It also handles the AX-25 protocol used in the communication.

Pin	Input/output	Name	Description
1			NC
2	I	Vdd	3.3V for digital circuits. This voltage is not possible to turn off.
3	I	0	0 V (power ground).
4	O	SDA_T	Telecommand data bus. Uses I2C protocol. This bus is connected to all subsystems. The commands sent from earth to the satellite are distributed via this bus.
5	O	SCL_T	Telecommand clock bus. The I2C protocol needs two busses; data and clock.
6	O	DGND	Ground for digital circuits.
7	I	SDA_D	Data bus. This data bus contains the information that is supposed to be sent down to earth. The bus connects the data-selector and the TNC. The TNC then distributes the data to the UHF and S-band transmitters using pin 11 and 12. It uses the I2C protocol.
8	I	SCL_D	The I2C clock bus for the Data bus (pin7).
9	O	Temp	Temperature sensor bus.
10	O	TXs	S-band Data. Contains the information which shall be sent to earth via S-band. Connects the TNC and the S-band transmitter. The AX-25 protocol is used and the baud rate is 9600.
11	O	TXu	UHF data. Contains the information which shall be sent to earth via UHF. Connects the TNC and the UHF transmitter. The AX-25 protocol is used and the baud rate is 9600.
12	O	TXS_en	S-band transmitter enable pin. This pin is used to start S-band transmission. The TNC handles this pin.
13	O	TXU_en	UHF transmitter enable pin. This pin is used to start UHF transmission. The TNC handles this pin.
14	O	RXv	This pin contains the VHF uplink data from the receiver. This pin is connected to the RJ-45 connector. This pin is for testing purposes.
15	I	Vbat	Battery voltage. This pin is used for beacon modulation. Beacon is used for tracking the satellite. The beacon signal has information about the battery status.
16	I	D_en	Digipeat Enable pin. This pin is set if the satellite has enough power to be used in digipeat mode.
17			NC
18			NC
19			NC
20			NC

7.6.1.7.3 Edge connector J3; AIS receiver and AIS OBDH board

This is a female 20 pin edge connector. This board contains the AIS receiver and the AIS microcontroller. The AIS (automatic ship identification system) uses a closed 162MHz frequency for receiving information from the ships. The AIS system is a commercial system for communication between ships and ship to shore. The information sent is ship ID and destination together with position, direction and speed. This shall be used to prevent collisions, to let the coast guards know more about the traffic off shore. The communication has so far been made with regular radio transmissions. The nCube AIS receiver is a test if it is possible to use satellites in the system, relaying information over a bigger area.

Pin	Input/output	Name	Description
1	I		NC
2	I	Vdd	3.3V for AIS receiver board. This voltage is possible to turn off.
3	I	0	0 V (power ground).
4	I	SDA_T	Telecommand data bus. Uses I2C protocol. The AIS system receives commands from earth via the telecommand bus.
5	I	SCL_T	Telecommand clock bus. The I2C protocol uses a clock bus together with the data bus.
6	I	DGND	Ground for digital equipment.
7	O	SDA_D	Data bus. Uses I2C protocol. This bus contains data which is supposed to be sent to earth. The pin is connected to the data selector.
8	O	SCL_D	The I2C clock bus for the Data bus (pin7).
9	O	Temp	Temperature sensor bus.
10			NC
11			NC
12			NC
13			NC
14			NC
15			NC
16			NC
17			NC
18			NC
19			NC
20			NC

7.6.1.7.4 Edge connector J4; ADCS and magnetometer board

This is a female 26 pin edge connector. The ADCS system (Attitude Determination and Control System) is the system that controls the satellites position. The ADCS system consists of two parts; the detections system and the adjustments system. The detection system is a series of LDR´s (Light Dependent Resistors). The ADCS microcontroller measures sunlight at the different sides at the satellite and calculates the position. The other part of the ADCS system is the adjustment system. There are two ways of adjusting the satellites position; the gravity boom and the magnetometers. The gravity boom is deployed after the satellite has left the POD. The boom can stabilize the satellite with an accuracy of about 15 degree. The magnetometers are used for fine adjustments. The magnetometers consists of three coils placed at the x, y and z axis. When magnetic fields are made around the coils (by current), it reacts to the earth magnetic fields and turns the satellite.

Pin	Input/output	Name	Description
1	I	VccM	6.5V for magnetometer. This voltage is possible to turn off.
2	I	Vdd	3.3V for digital circuits.
3	I	0	0 V (power ground).
4	I	SDA_T	Telecommand data bus. Uses I2C protocol. The ADCS system receives commands from earth via the telecommand bus.
5	I	SCL_T	Telecommand clock bus. The I2C protocol uses a clock bus together with the data bus.
6	I	DGND	Ground for digital components.
7	O	SDA_D	Data bus. Uses I2C protocol. This bus contains data which is supposed to be sent to earth. The pin is connected to the data selector.
8	O	SCL_D	The I2C clock bus for the Data bus (pin7).
9	O	Temp	Temperature sensor Bus.
10	I	I_A	Sun exposure on panel A. Sun intensity is measured using an LDR.
11	I	I_B	Sun exposure on panel B. Sun intensity is measured using an LDR.
12	I	I_C	Sun exposure on panel C. Sun intensity is measured using an LDR.
13	I	I_D	Sun exposure on panel D. Sun intensity is measured using an LDR.
14	I	I_Z	Sun exposure on panel Z. Sun intensity is measured using an LDR.
15	I	I_N	Sun exposure on panel N. Sun intensity is measured using an LDR.
16	I	AGND	Ground for analog circuits.
17	O	Vma+	Magnetic coil A+. Connection for the magnetic coils used for fine adjustments of the satellites position.
18	O	Vma-	Magnetic coil A -
19	O	Vmb+	Magnetic coil B+
20	O	Vmb-	Magnetic coil B -
21	O	Vmz+	Magnetic coil Z+
22	O	Vmz-	Magnetic coil Z -
23			NC
24			NC
25			NC
26			NC

7.6.1.7.5 Connector J5; Battery

This is a male 8 pin double row connector. There are two batteries connected in parallel in the satellite. There is a temperature sensor glowd on the batteries.

Pin	Input/output	Name	Description
1	I/O	Bat+	Battery +. Connected to the anode on battery A.
2	I/O	Bat+	Battery +. Connected to the anode on battery B.
3	I/O	Bat-	Battery -. Connected to the cathode on battery A.
4	I/O	Bat-	Battery -. Connected to the cathode on battery B.
5	I	Vdd	Vdd for temperature sensor. The digital temperature sensor needs 3.3V for operating.
6	O	Tbat	Data bus for battery temperature.
7	I	DGND	Ground for digital circuits (temp sensor).
8			NC

7.6.1.7.6 Connector J6; RJ-45 jack

This is a male 8 pin double row connector. This connector is used for communication with the satellite when it is on earth. The most important values in the satellite are connected to this jack. To be able to find errors and evaluate the system, communication is needed. A jack is a simple way of accessing data in the satellite.

Pin	Input/output	Name	Description
1	O	TXu	UHF downlink data. Data to be sent to earth with the UHF transmitter. Using 9600 baud and the AX-25 protocol. This data is supposed to be sent from TNC to the UHF transmitter.
2	I	RXv	VHF uplink data. This is the data sent from earth via the VHF band. Uses 9600 baud and the AX-25 protocol. This data is supposed to be sent from the VHF receiver to the TNC.
3	I	SDA_T	Telecommand data bus. Uses I2C protocol. All telecommand (from earth) to the different parts of the satellite is sent via this bus.
4	I	SCL_T	The I2C clock bus for the Telecommand data bus (pin3).
5	I	DGND	Ground for digital circuits. For testing ground failures.
6	O	SDA_D	Data bus. Uses I2C protocol. This pin is used for sending data to the TNC. For testing purposes.
7	O	SCL_D	Clock I2C bus for the data bus (pin 6).
8	NC	NC	

7.6.1.7.7 Connector J7; Solar panel D

This is a 6 pin singe row male connector. The solar panel on the D side is the last side to be assembled. That is why only this side has a connector. The other sides are soldered directly to the backplane to save space. The solar panels have a temperature sensor and a LDR circuit. The temperature sensors are placed on the inside of the structure. The structure in solar panells is made from regular PCB´s. That makes it easy to route connections and to make sensor layout.

Pin	Input/output	Name	Description
1	I	Vd+	Voltage +. This pin is connected to the anode of the solar cell.
2	I	Vd-	Voltage -. This pin is connected to the cathode of the solar cell.
3	I	Vdd	3.3V for digital temperature sensor. The sensor needs voltage for operating.
4	O	T_D	Data bus for solar cell temperature.
5	I	DGND	Ground for digital circuits.
6	O	LDRd	Output for the LDR circuit on D side. This is used by the ADCS system for calculating the satellite position.

7.6.1.7.8 Connector J8; Flight pin and LDR on side N

This is a 6 pin single row male connector. The flight pin is a switch which is turned on right before the launch. It is the connection between the cathode of the battery and the rest of the satellite. When the flight pin is off, the entire satellite is dead. The pin is switched on manually. The flight pin uses two four pins, two for + and two for -, that is because off the big currents that could appear directly at the batteries. The flight pin connector also include the pins for the LDR on side N. The only reason to us the same connector as the flight pin is to save space. The flight pin is placed on the N side as well.

Pin	Input/output	Name	Description
1		F1	This pin shall be connected to the cathode of the battery and via the jumper to the flight pin.
2		F1	This pin shall be connected to the cathode of the battery and via the jumper to the flight pin. (paralleled)
3		GND	This pin is connected to power ground and via the jumper to the flight pin.
4		GND	This pin is connected to power ground and via the jumper to the flight pin. (paralleled)
5	I	LDRn	Output for the LDR circuit on N side. This is used by the ADCS system for calculating the satellite position.
6	I	AGND	Analog ground for LDR circuit.

7.6.1.7.9 Connector J9; Gravity boom and antenna release

This is a 5 pin single row male connector. The jumper is connected to the gravity boom release and the antenna release systems on N-side. The release systems consist of a piece of nicrome wire that will glow and burn off some fishing wire. The fishing wire is holding the antenna/gravity boom. There are four nicrome wires, two for the gravity boom and two for the antenna release, for redundancy. The gravity boom is released by a telecommand from earth. The antennas are released by the 555 timing circuit, a specified time after the satellite has left the POD. This system is completely separated from all other systems, that is because in needs to be completely fail safe.

Pin	Input/output	Name	Description
1	O	VbA	Boom release A. Glows the nicrome wire A, releases the gravity boom.
2	O	VbB	Boom release B. Glows the nicrome wire B, releases the gravity boom. (redundancy)
3	O	VbC	Antenna release C. Glows the nicrome wire C, releases the antennas.
4	O	VbD	Antenna release D. Glows the nicrome wire D, releases the antennas. (redundancy)
5	O	GND	Ground for release systems.

7.6.1.7.10 Connectors J10 to J13; Solar panels A, B, C and Z

These connectors are soldered directly to backplane. They have 6 pin each and look exactly the same as J7 but with the difference that they are soldered.

Pin	Input/output	Name				Description
		J10	J11	J12	J13	
1	I	Va+	Va+	Va+	Va+	Voltage +. This pin is connected to the anode of the solar cell.
2	I	Va-	Va-	Va-	Va-	Voltage -. This pin is connected to the cathode of the solar cell.
3	I	Vdd	Vdd	Vdd	Vdd	3.3V for digital temperature sensor. The sensor needs voltage for operating.
4	O	T_A	T_B	T_C	T_Z	Data bus for solar cell temperature.
5	I	DGND	DGND	DGND	DGND	Ground for digital circuits.
6	O	LDRa	LDRb	LDRc	LDRz	Output for the LDR circuit on D side. This is used by the ADCS system for calculating the satellite position.

7.6.1.7.11 Connector J14; Kill switch

This connector is soldered directly to the backplane. The kill switch has 4 pins; two switches are used for redundancy. The kill switch is turning on the satellite from being idle in the POD. The kill switches are placed on top of the satellite and are turned on the moment the spring separates the satellite from the POD. The switch is connected between the battery and the unregulated voltage bus.

Pin	Input/output	Name	Description
1		K1+	Kill switch 1+. Connected to the battery.
2		K1-	Kill switch 1-.Connected to the unregulated voltage bus.
3		K2+	Kill switch 2+. Connected to the battery. (redundancy)
4		K2-	Kill switch 2-. Connected to the unregulated voltage bus. (redundancy)

7.6.1.7.12 Connector J15; Magnetic coils

This connector is soldered directly to the backplane. The connector has 6 pins. The ADCS system uses magnetic coils for fine adjustments of the satellite position. There are tree coils with two connections each.

Pin	Input/output	Name	Description
1		Vma+	+ connection of magnetic coil on side A
2		Vma-	- connection of magnetic coil on side A
3		Vmb+	+ connection of magnetic coil on side B
4		Vmb-	- connection of magnetic coil on side B
5		Vmz+	+ connection of magnetic coil on side Z
6		Vmz-	- connection of magnetic coil on side Z

7.6.2 The power PCB

When the distributed power system (DSP) PCB was made, all of the components where chosen and tested separately. The job here was to put them in a system, choosing architecture to build it on and of course routing the traces with reliability in mind.

7.6.2.1 The DPS architecture onboard the nCube satellite

On the nCube satellite bits of all the structures discussed the theory chapter are used.

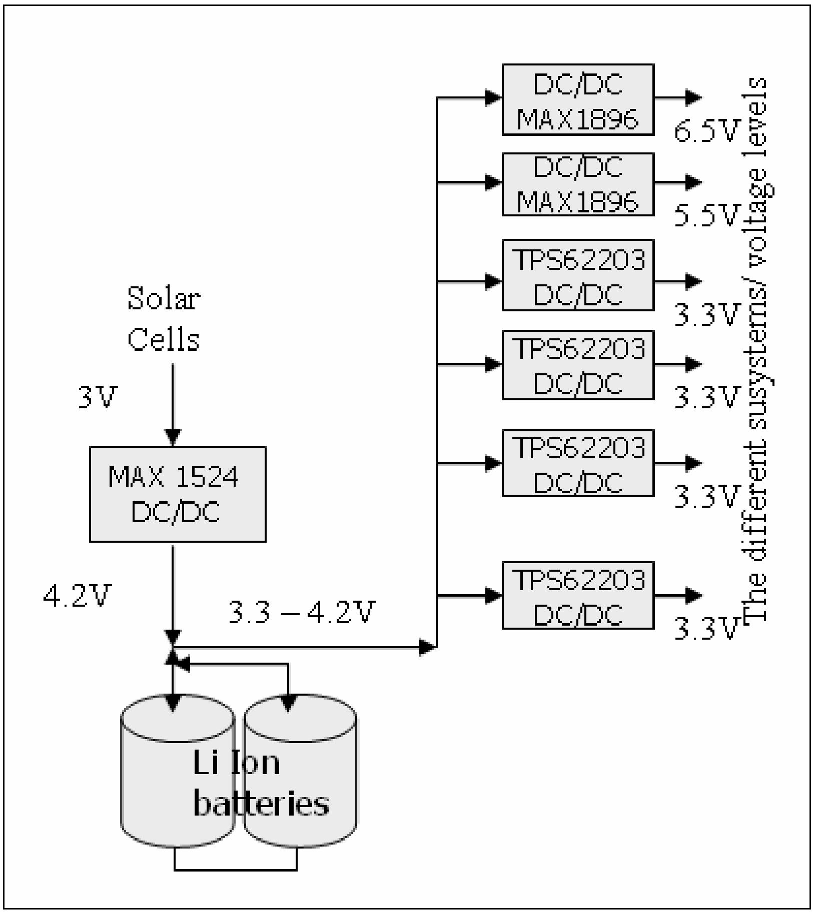


Figure 94: Showing a block schematic view on the distributed power system on board the nCube satellite.

Cascading
Cascading has been used, between the solar cells and the Battery/ bus; there is a DC/DC converter (max1524) which raises the voltage from 3V volts to 4.2V. When this was designed power distributions benefits wasn't in mind, but simply to be able to charge the batteries. Now seeing the benefits this brings means that the power bus is reliable due to loss and noise.

Source splitting
Source splitting is also used; but not with separate power processor units (PPU). The solar cells, the batteries and the subsystems are coupled on the same bus. This makes it possible to

drain power directly from the solar cells or directly from the batteries. This gives redundancy if the solar cells are in the shadow or if the batteries are fully charged.

Load splitting

Load splitting is also used. Almost every subsystem has its own DC/DC converter. There are none on-board DC/DC converters; they are all placed on the power PCB. But the distance to the load is very small so it wouldn't make a big difference. It's more of a benefit when all of the power components are shield from the other "signal components" with a ground plane between (this is discussed under PCB layout). The DC/DC converter will deliver reliable power with correct voltage level and high power density to the subsystems.

The system would be much more robust if each subsystem where assigned with two or three DC/DC converters in parallel. Each of this converters should be able to handle the load by it self's; so if one of the converters fail; there will be a second or third in hand to take over the load. This could even be a benefit because the stress on each component will be reduced depending on the output voltage on each converter.

With this structure and with the battery as a giant conductor the power buss on board the satellite should be robust considering efficiency, noise and power density.

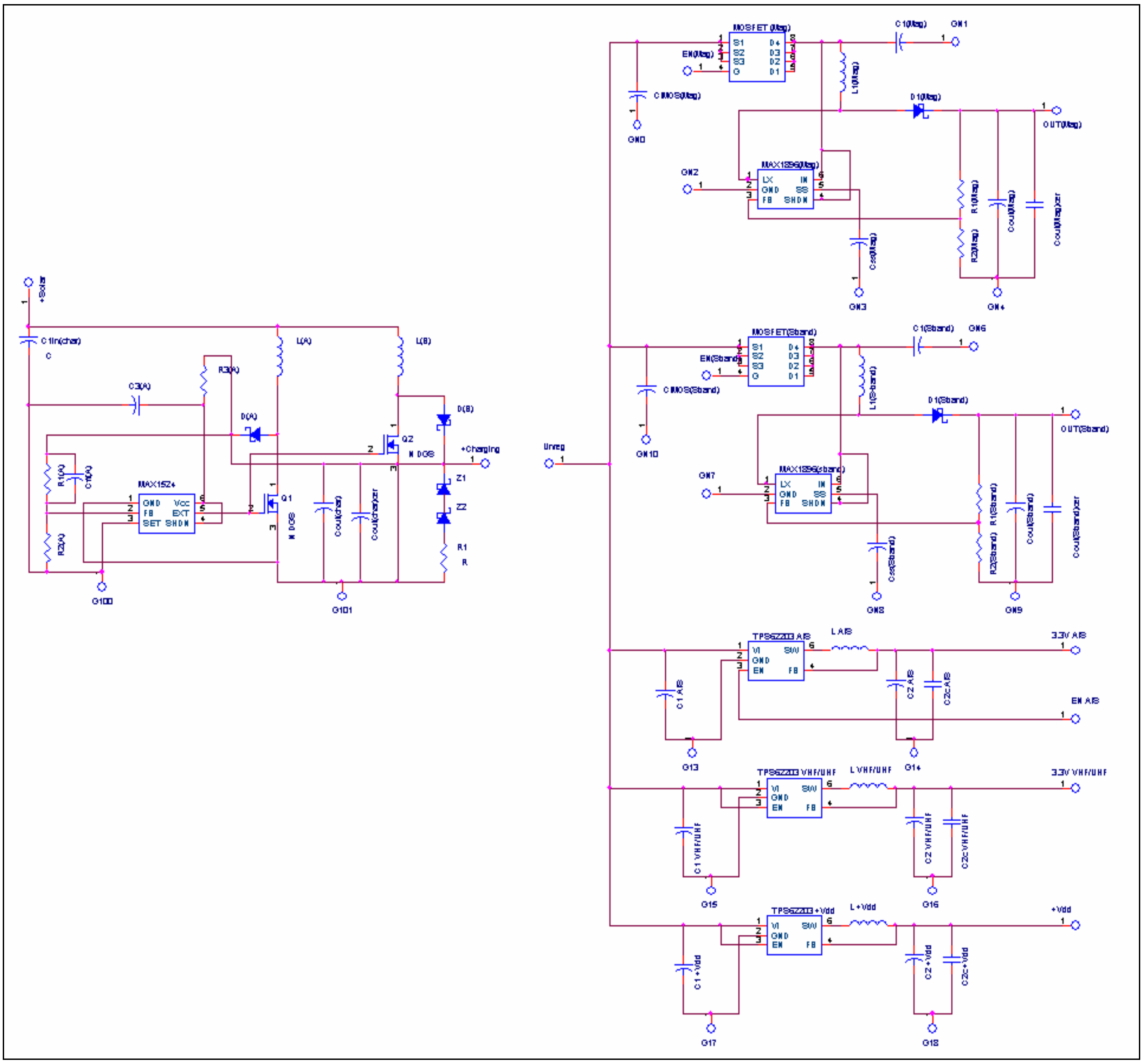


Figure 95: Capture layout for the power PCB

The capture file shown above of the power PCB, shows how the different DC/DC converters are put together with a shared bus. On this layout there is a gap between the MAX 1524 DC/DC converter and the DC/DC converters supplying the subsystems. This is where the traces go to the backplane to be connected to the sensors before returning to the Power PCB. This is done to reduce the number of connections between the two cards, and separate the other components from the components on the power PCB.

The PCB layout shown below is what the circuit board will look like. The four rectangles are space where the circuit board will be attached to the structure. The power PCB together with the backplane will function as the mother board in PC, therefore this relatively large space to install.

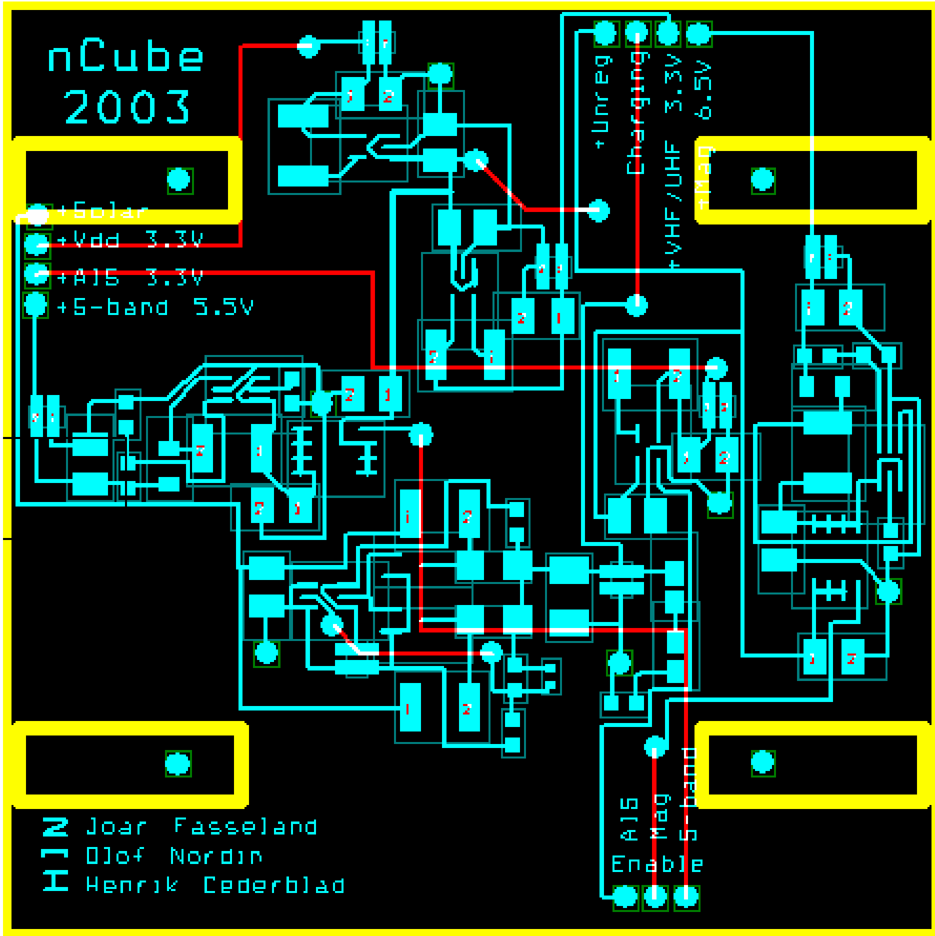


Figure 96: Shows the layout on the power PCB

There are 11 connection points on the PCB. Here is a briefer description of the connectors.

Start on the left side of the picture (which is the D side on the satellite), there are four connectors. Listing from the top:

1. +Solar; this is node that the solar cells are connected through the backplane. This node is also the input voltage on the MAX1524 DC/DC converter that boosts the solar voltage to 4.2V.
2. +Vdd 3.3V; is the node where the output from the TPS62203 DC/DC converter supplying the subsystems attached to Vdd through the backplane with a 3.3 voltage level. Systems connected to the Vdd node is: PMU, sensors, TNC and OBDH. The load ability on this converter is 300mA/ 3.3V. This system isn't controllable so the enable pin is hard wired to Vcc.
3. +AIS 3.3V; is the node where the output from the TPS62203 DC/DC converter supplying the AIS receiver subsystems through the backplane. The load ability on this converter is 300mA/ 3.3V.
4. + S-band; is the node where the output from the MAX1896 DC/DC converter supplying the S-band transmitter subsystem through the backplane whit a 5.5V voltage level. The load ability on this converter is 450mA/ 5.5V.

On the bottom side of the picture (which is the Nadir side on the satellite), there are three connectors. Listing from the left:

5. AIS enable; this is the enable pin on the TPS62203 DC/DC converter. This is the node that makes it possible for the PMU and TNC to switch on/off the AIS receiver if necessary. This enable pin is a true shut down pin.
6. S-band enable; this is the enable pin on the MOSFET connected to the Vcc on the MAX1896 DC/DC converter. This is the node that makes it possible for the PMU and TNC to switch on/off the S-band transmitter if necessary. This enable pin together with the MOSFET is a true shut down pin.
7. Mag enable; is the same as number 6 (S-band enable), only it is controlling the magnetometers.

On the top side of the picture (which is the Zenith side on the satellite), there are four connectors. Listing from the Right:

8. +Mag 6.5V; is the same as number 4 (+ S-band), only it is supplying the magnetometers with a 6.5V voltage level. The load ability on this converter is 250 mA/ 6.5V.
9. +VHF/UHF; is the same as number 2, only it is supplying the UHF transmitter and UHF.
10. +Charging; is the output voltage 4.2 from the MAX1524 DC/DC converter and is the charging source between the solar cells and the batteries.
11. +Unreg; is basically the same node as charging, only the trace has been through the sensors placed on the backplane. This is the starting point of the power bus on the power circuit board.

7.7 Power management unit

The program is made in developed using Assembly. It is built with a round robin, with interrupts software architecture. There is also a watchdog timer implemented in the processor. Watchdog timer is a timer that runs in the background and gets restarted after a fixed duration. If the watchdog timer doesn't get reset on time; the watchdog timer resets the entire processor. This is implemented incase an unexpected error in the code occurs.

7.7.1 Introduction to the PMU program code

The main loop consists of the six different main tasks:
Check commandos
Reading IU (Current and Voltages)
Reading temperature1 (Internal temperatures)
Reading temperature2 (Solar cell temperatures)
Control sense values
Write to log

It continuously runs through the blocks shown in the picture above. First it checks for any received commands from the TNC I2C bus; then it continues too read the current, voltage and the two lines of temperature sensors. Then all the collected data gets controlled and logged every 10th minute.

The interrupts are:
I2C commando
Temperature timer timeout

There are also several subroutines.
Subroutines:
Send status
Send Log
Turn on or off subsystems
Send I2C
Read EE
Write EE
Read FLASH
Read FLASH table

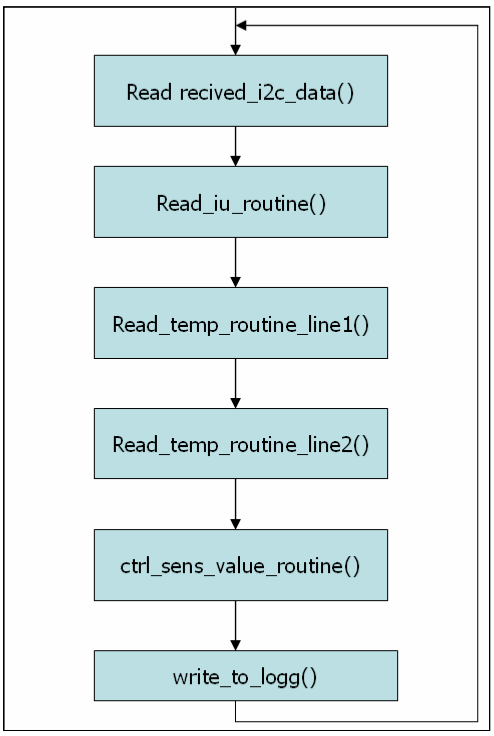


Figure 97: The main routine, Round Robin structure.

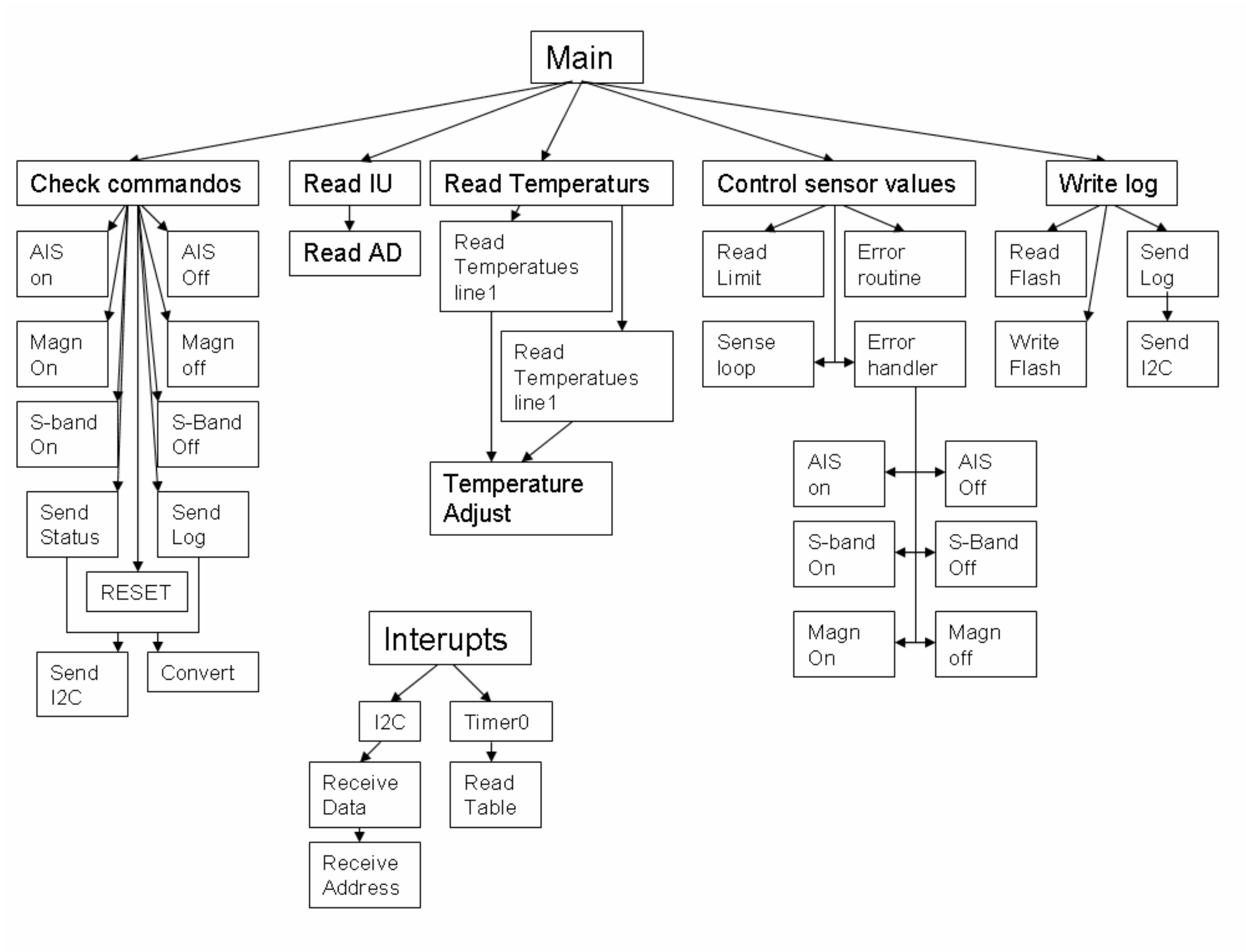


Figure 98: Function tree of the program code.

Housekeeping data

All sensor values that are gathered from the different sensors are saved to RAM. This together with the time and a status byte is the housekeeping data.

The housekeeping data consists of:

2 byte clock hour & minutes
11 temperature values
10 current values
8 voltage values
1 error byte

The housekeeping data is sent to earth as unformatted data. The data has to be decoded on earth to get the proper values. See enclosure Power management code (last page).

7.7.2 Explanation of the program code

Reading AD is where all the voltage and current levels are collected. This is made by the built in A/D converter. There are a built in switch and two external switches. To port 1 on the internal switch a switch is connected which takes care of all voltage measuring points. Port 2 is also connected to an external switch, this together with port 3 and 5 is connected to the current sensors. Port 4 on the A/D is connected to a voltage reference circuit.
The external switches are controlled by 3 digital outputs on the processor.
The digital value from the A/D converter is a 12 bit value which is truncated to an 8 bit value to save memory space and communication time.

Reading temperature is made by a starting a timer that hold track of the time between the pulses from the temperature sensors. When the program is sending a trig pulse, the sensors are started, and the program is waiting to answer from the sensors. The only way of getting the program out of this loop is by answer from the sensors or by the "temperature timeout timer" that is started at the beginning of this routine. This timer is implemented as an extra safety if some of the sensors wouldn't answer; the program won't when it's in an endless loop. Instead there will be an interrupt and the value hFF will be loaded into the memory instead of the temperature. hFF is not a valid temperature and can easily detects as an error.
Because of the different answering time of the sensors, the "temperature timeout timer" is loaded with different values depending on which sensor that didn't answer. This loop runs two times but with different pins and with different number of sensors.

Temperature loop 1 reads temperatures from:
Batteries
ADCS (Attitude Determination Control System)
AIS
TNC (Telecomand)
UHF radio
S-band radio

Temperature loop 2 reads temperatures from:
Solar cells A-side
Solar cells B-side
Solar cells C-side
Solar cells D-side
Solar cells Zenith side

The processor is running with a 2MHz crystal, and that with the internal prescaler, means that each program step takes 2uS.

The time is counted with a timer (Timer1) which has a 16 bits register. To save memory place it is converted to an 8 bit register.
The temperature sensor is designed for temperatures between -40° and +125° C, this makes the smallest number of time steps to:
5µ*(273-40)/2=582 steps
Maximum steps are:
5µ*(273+125)/=995 steps

By subtract 582 from all measured values, there can be saved some space which make the possible temperature between 0-413 steps. By divide this with 2, it can be saved to 1 byte. When dividing it with 2 the accuracy on the temperature will go from 0,4°C/bit to 0,8°C /bit.

7.7.2.1 Check commandos

Check commandos checks if there is any commando that should be executed. The first thing that is done is to check if any of the send routines has been interrupted, if they are and there are ok to send on the I2C buss, one of these routines is called. When a new commando is received the commando byte is written to. If this byte isn't empty the program continues and checks which commando that has been received.

7.7.2.2 Control sense values

Control sense values are a routine for checking that the measures values are between the limits. If any value is out of the limit, a flag will be set. If the system that is outside the limit can be turned off, this will be done otherwise only the flag will be saved. By reading the flags the error can be found. There is a table of maximum and minimum values for each sensor in which they are controlled against. If any of the values have excided there limits an error routine starts and do what's necessary; a log is also created and sent to earth.

		Limits adr		Value (scaled)		Value real [V]	
Sensor	Ram adr	min	max	min	max	min	max
U_bat	h4A	hB4	hB6	hA9	hD7	3,3	4,2
U_dd	h4B	hB8	hBA	h9F	hB3	3,1	3,5
U_s	h4C	hBC	hBE	hA6	hC0	6,5	7,5
U_mag	h4D	hC0	hC2	hBC	hDE	5,5	6,5
U_ais	h4E	hC4	hC6	h99	hBC	4,5	5,5
U_uhf	h4F	hC8	hCA	hBC	hDE	5,5	6,5
U_vhf	h50	hCC	hCE	h99	hBC	4,5	5,5

Figure 99: Shows an extract from the table that the PMU controls the sensor values against.

When value has gone back to normal, the subsystem is allowed to be turned on again on command from TNC. The power management system is only allowed to turn off systems. The control of the digipeat pin is also done here, if the battery and solar cell voltage is above the limit values it is turned on. Otherwise the digipeat is turned off.

7.7.2.3 Log routines

Write to log is a routine that writes the latest house keeping data to the log every tenth minutes. To now when to write to the log, there are a memory space where the time is saved from the last writing. By comparing this value to the current time the program know when to write to the log. If there have gone ten minutes since the last writing the new values is logged and the current time is saved as "last written time memory space".
Sending log is a routine that will be executed when a send log command is detected from TNC.

The log is a circular loop with 4896 byte memory space. This means the when all 4896 bytes has been used, the first (and oldest) values is written over. The housekeeping data consists of 32 byte data.

This means that the log keeps logged data for 25 hours. There are two pointers that are used for keeping track of the logged data. One pointer points to the first not sent block, and the other pointer points to the last written block. When a block should be written to the log, it is written to the place where the second pointer points. The pointer is then stepped up to next block place. When the log will be sent it sends from where the first pointer points, and then this pointer is stepped up en block until the first and the second pointer is pointing to the same place. When this happens the program knows that all logged data is sent.

The log is saved to the program flash and the pointers are saved to the internal EE-PROM. By doing this, the log will not be affected of a restart or power loss in the processor.

7.7.2.4 Communication

The communication between the different microcontrollers in the satellite is done with an I2C bus (Inter-Integrated Circuit bus). This is a 2 wire bus, clock and data line. The I2C uses master and slave controllers with addresses. There can only be one active master on the bus at the same time, when a master wants to take control of the bus, it pulls the data line low while the clock line is high. This is a way to take control over the bus, when one master has taken the bus, no one else is allowed to do anything on the bus without being asked to do so by the master. When the master I finished it releases the clock line when holding the data line low, and the releasing the data line, this says that the bus is free for any other to take control over it. The communication starts with an address byte here the first 7 bits are the address and the last bit is the Read/Write bit that is telling if the master want to read or write to a slave. After that the data is sent byte by byte. After each byte a acknowledgment is sent back from reader to verify that the byte is received. If a master wants to communicate to more than one slave, without letting the buss free, it can send a repeated start condition and a new address to communicate to a new slave.

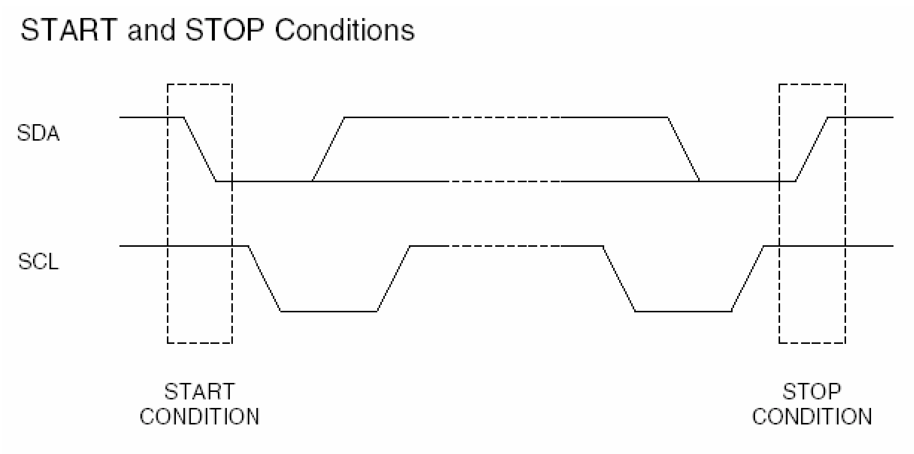


Figure 100: The start and stop conditions for the I2C communication.

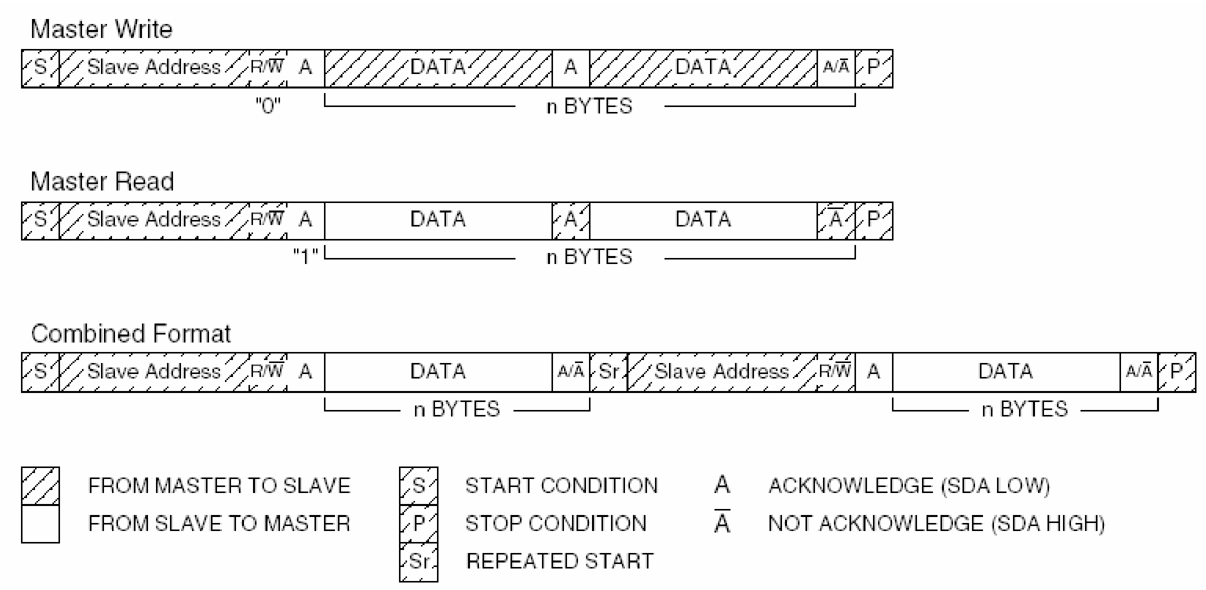


Figure 101: The principle of I2C communication.

The power management uses the I2C data buss to receive commands and time from Telecommand, and to send housekeeping data to the radio trough TNC.

Sending log and status use the I2C to send the saved values. They both execute on commando from TNC. Sending log is sending the saved log (se Log routines), and the send status is sending the latest measured values from the sensors. When sending data to TNC each byte is loaded from log or RAM, then it is converted to valid ASCII values by first BCD coding it and the convert every sign to ASCII sign.

When sending the data to TNC, first the start condition is sent, and then the address, and then the value is sent, which now consists of three ASCII signs. Then a stop condition is sent and the loop starts again until all data is sent.

7.7.2.5 Turning on and off subsystems

Because of the solution with a XOR gate to each enable line to the subsystems, there are extra inputs that detect if the enable is high or low. If the processor wants to turn of a system, it checks if the enable port is in right state. If it is wrong, it toggles the pin that is connected to the XOR gate. This makes the XOR gate toggle its output and the subsystem will change state.

7.8 Satellite simulation

To be able to test the power system, one diploma task is to build a simulator with dSpace and Simulink/Matlab.

The purpose of this simulator is to test the power system and the batteries. This is made by connecting the power system of the satellite to dSpace. dSpace consists of an I/O card with analogue and digital inputs and outputs. Between dSpace and the satellite there is an Interface card. This simulator will simulate the solar cells and the load from the different subsystems.

The simulator should simulate the solar cells when the satellite is in orbit around the earth. The simulator should also take efficiency lost from temperature in consideration.

7.8.1 dSpace

dSpace is an company that manufactures real time test systems also called hardware in the loop. The products that has been used in this work is dSpace DS1102 which is a circuit board with an own real time processor and I/O´s, this board is connected to the PC ISA bus. To control and program the dSpace processor, the “control desk” software is used. This software is built to work together with Matlab and simulink. All the simulation and algorithms is made in simulink.

7.8.2 Interface card

To be able to use the signals from dSpace, an interface card had to be made.
The signals that will be used between dSpace and the satellite are three digital outputs, three analogue inputs and one analogue output. The digital outputs are used to simulate different loads, UHF, VHF and magnetic coils. The analogue inputs should be used to measure the current and voltage from the simulated solar cells and the output voltage from the magnetometer/magnetic coils DC/DC converter on the satellite. The analogue output is used to simulate the solar cell voltage.

The different loads from the subsystems are simulated by connecting a resistor to each power output of the satellite. Some subsystems are always turned on or are controlled by the PMU (Power management unit), and that's why some of the resistances are directly connected to satellite. Other systems are internally controlled and to simulate these, there are three digital signals from dSpace that controls these systems. To get galvanic protection there is an optocoupler connected to each digital output from dSpace.

System	Resistor [ohm]	Load [mA]
Magnetometer	325	20
Magnetic coils	250	25
S-Band	15	390
AIS	110	30
UHF RX	65	50
VHF	40	80
UHF TX	10	400
Vdd	250	13

Figure 102: Resistors used as simulated loads.

To amplify the current from the optic switches, there are MOSFET transistors connected to them. The gates from these transistors are connected to the digital outputs from the optocoupler switches. The analogue output signal is connected to an OP amplifier to amplify the current.
This OP amplifier is connected as a simple current amplifier.
To get the correct output voltage from the OP there is a connection between the OP output and the first analogue input on dSpace. This is to compensate for voltage loses in the OP. To measure the output current, the second analogue dSpace input is connected to the solar cell current measure circuit that is mounted in the satellite. The interface card needs to be connected to a ±12 Volt source.

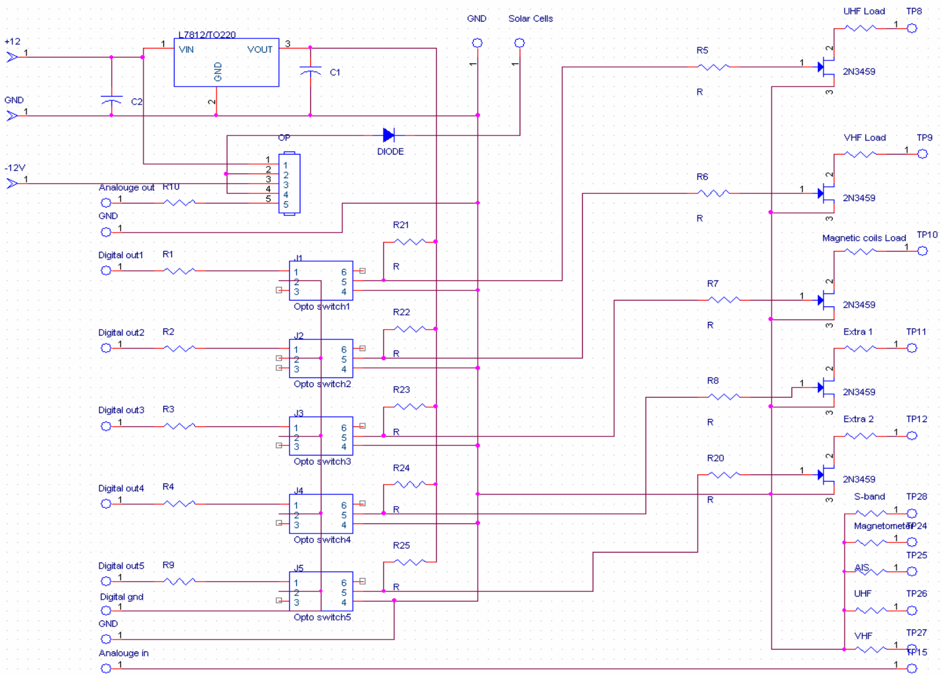


Figure 103: Shows the circuit layout of the interface card

7.8.3 Simulation of solar cells

The first thing to do was to test the real solar cells. By testing those with different load, a function can be made between the output current and voltage (in constant temperature). This function is then used to simulate the solar cells depending on the load.
The same thing can be made by testing the cells with different temperature with a constant load. This function is made by taking the tested values and make an numerical third and fourth grade function, by making a graph of these it shows how accurate these functions is due to the real measured values. There where no mayor difference between the third and fourth grades functions, but the fourth was used because there's no more work with implementing it. There are several programs for calculating a fourth grade function from a series of values. In this case, Casio's built in calculator program was used. This resulted in I fourth grade function:
V=-5,231e^-14*x^4+1,3283e^-10*x^3-7,96e^-8*x^2-1,345e^-4*x+3,222

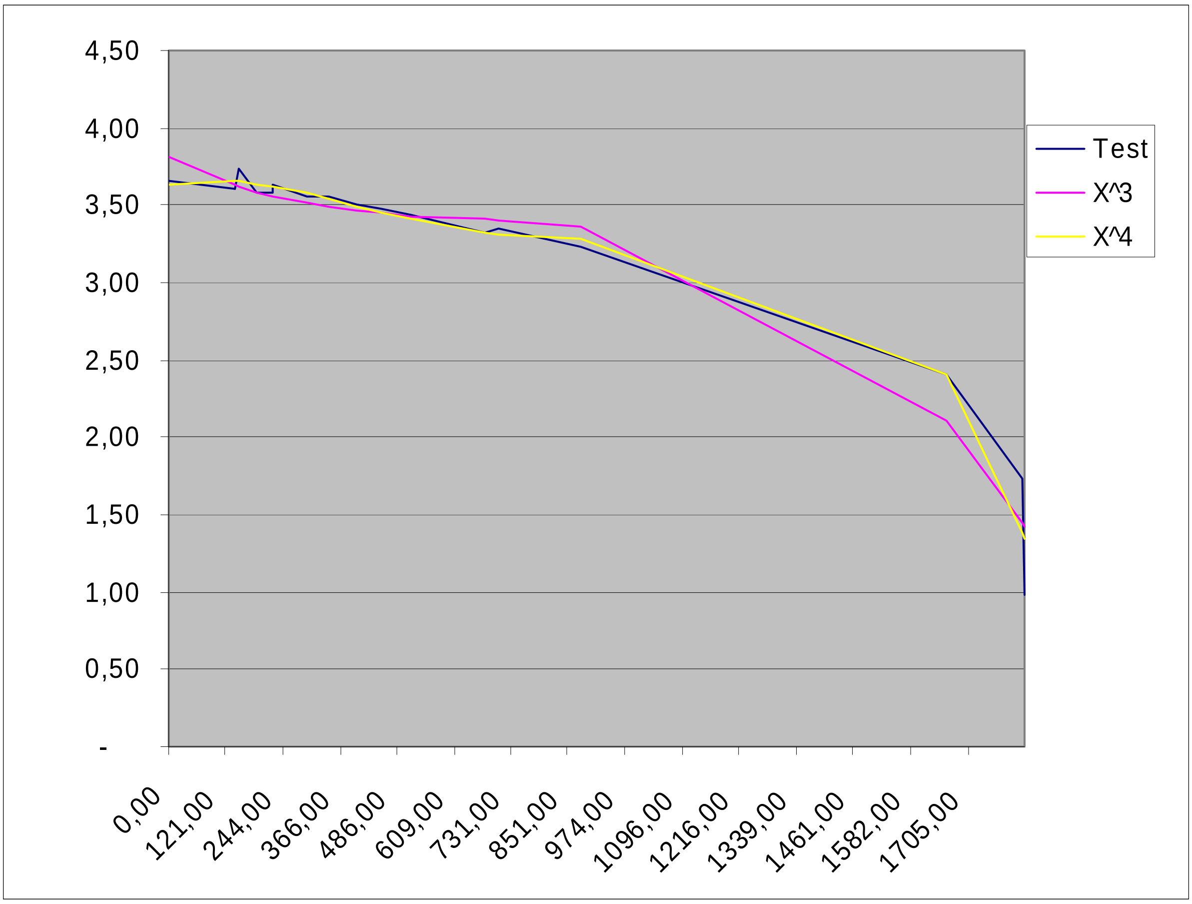


Figure 104: shows the calculated functions and the measured characteristic of a solar cell.

One problem with simulating temperature is the in the beginning the satellite will tumble free in space, this means that a random side is against the sun for an unknown time. When the cell is in the sun they will be heated up by the sun, the temperature will be dependent on the time that the cell is against the sun. Then the cells will be cooled down in shadow. If the satellite is rotating fast the temperature will be even on at least four sides, and if it is rotating slowly, the cells will be hotter under the working time, which gives lower efficiency. Another consideration is that only 5 sides have solar cells, if the 6´th side is against the sun, there will be no energy delivered from the cells. The temperature on the solar cells is also unknown until it has been tested, and the only way to test this is to send up the satellite. This means that until the satellite is lunched, only estimates of the temperature can be made. Another unknown factory is the efficiency of the solar cells, the only given number there are, is the efficiency given by the manufactory of the cells, if it is right is to be determined.

Ageing is something that affects the cells as well. But because of the life time of this satellite is relatively short, this is no mayor consideration, but it will be affect the simulation anyway.

The last and most difficult is to simulate the amount of light that is hitting the solar cells. There can be between 0 and 3 cell-side facing the sun at the same time. But when the satellite is stable, there should always be at least one side with cells facing the sun. Te only time there is no sun at all is when the satellite is in shadow behind the earth. The orbit will take about 96 minutes and maximum 16 of these minutes will be in shadow.

Minimum power, with sun on the cells, is in the first and last 6.8 minutes before entering or returning from the earth shadow and the sun is shining on the bottom of the satellite and on only 1 cell-side.

Earth radius: 6378
Satellite height: 700
Satellite orbit radius: 7078

Angel = arc cos(6378/7078)=25.6º
Time for part sun: 5760*25.6/360=409 sec = 6.8min

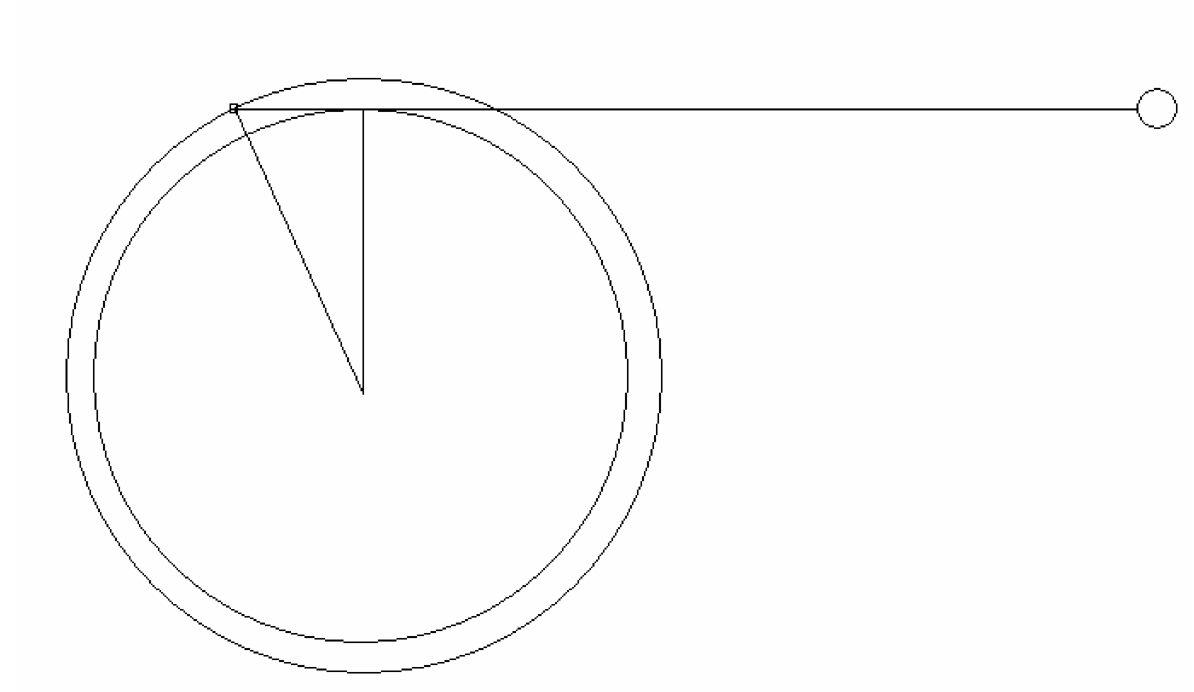


Figure 105: Shows the satellite when returning from shadow

Minimum power:
Sin 25.6 = 0.43A

Maximum power:
By calculating the angel when three different sides are facing the sun with the same area, the maximum energy is found. If each side of the satellite has the length 1, makes the length of A = √ (1+1) = √ (2) and side B=√ (1+1+1) = √ (3). Knowing this, angular φ and ω are possible to calculate. ω = arc sin (1/√ (2)) = 45° and φ= arc sin (1/√ (3)) = 35.26°. This makes the angel that the sin will hit the sides to 180-35.26 = 144,74.
3*sin 144.74 = 1.73A
A is the amount of power from 1 cell side facing the sun with 90 degrades.

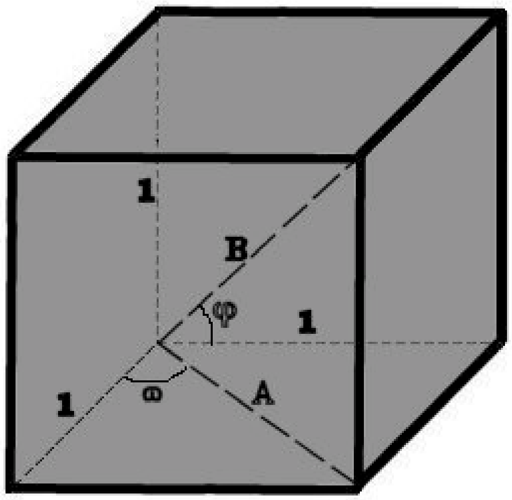


Figure 106: Shows the angels for maximum area

These different things affect the cells in different ways. The temperature affects the output voltage from the cells, while the amount of sunlight affects the maximum current that can be delivered from the cells.

7.8.4 Simulink

The simulation is bases on data generated from simulink.
Simulink is an add-on program to Matlab that is useful, it is based on a block construction where different blocks can be added and connected to build the simulation.

To simulate the solar cells there is first a timer that counts from 0 to 5760 seconds (96 minutes). Then the counter starts from 0 again. From 0 to 3660 sec (61 min) the satellite is in the sun, the last 2100 sec (35 min) the satellite is shadowed by the sun. This is the worst case orbit and probably not the case of the real satellite. A switch with a switching level at 3660 is used to simulate the different between sun and shadow. When the timer is under 3660, the switch is in sun mode and let the simulated sun pass through the switch. When the timer has counted up 3660 the twitch switches to shadow mode and a constant voltage of 0.1 Volt is on the output. This is made because the earth will also affect the solar cells with some energy. When the satellite is in the sun, cells will be heated up and the output voltage will drops. To simulate this, the voltage drops with 1% each minute for the first ten minutes, and then gets constant. When the satellite is in the sun, it will rotate and the angels of the cells facing the sun will vary. To simulate this difference some sinus and cosines waves are added to the input current. This will simulate the difference in possible output current.

In the simulation it is assumed that the gravity boom is deployed and the satellites Nadir side is always facing the earth. The rotation around the centre axis can be set in the simulation. There will be possible to get maximum power two times in every orbit, that's when the sun is shining with the angel of 144.74º on the satellite. This is if the angel between the satellite orbit and the sun is 180º. The simulation is made of a one function that gives less power in the beginning and the end of the lighted orbit. Another function is making the power increasing and the third function takes care of reducing the power in the middle of the orbit.

The characteristic of the power variations from the solar cells is depending on the angel between the sun and the satellite orbit. Worst case is 180º which gives 35 minute of shadow and big variation in the rest of the orbit of 0.43 – 1.73 solar array areas.

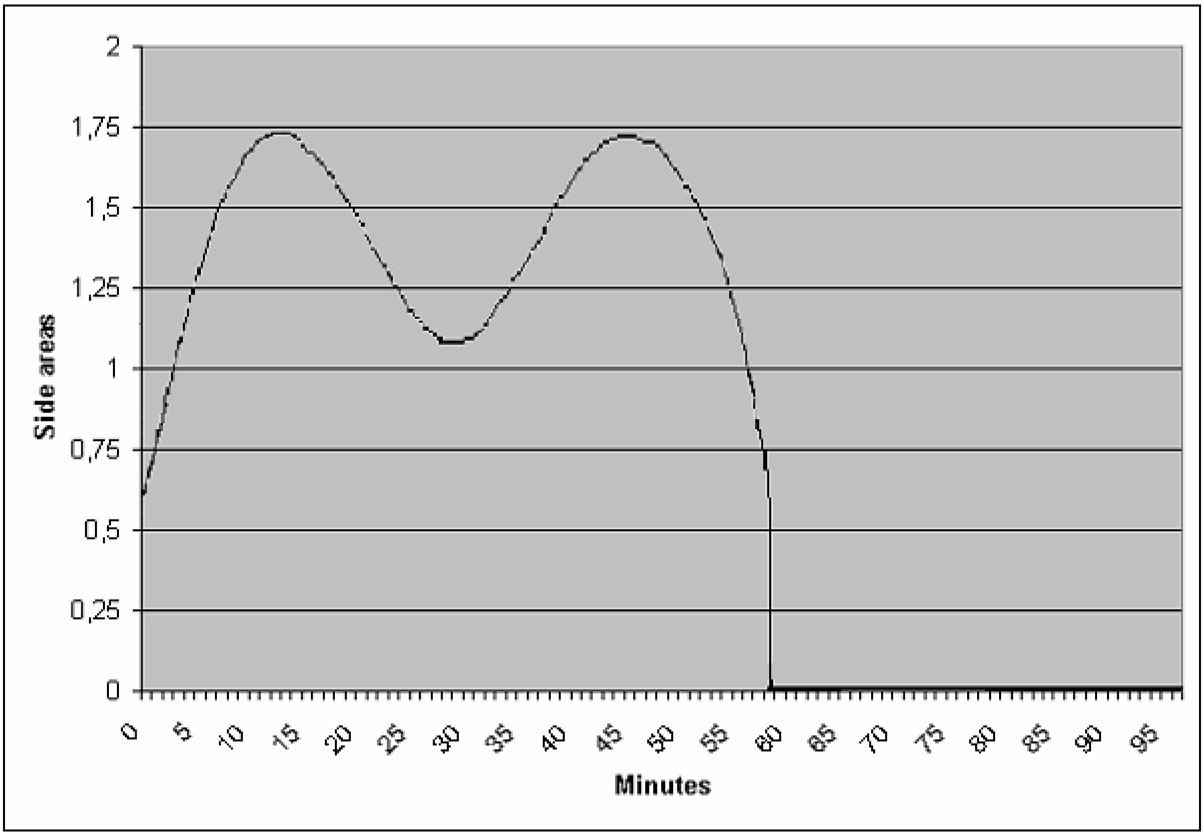


Figure 107: Shows a drawing of energy available from solar cells in a 180º orbit

Best case is when the sun is shining on the side of the satellite with a 90º angel between the sun and the orbit. This gives no shadow and a very stable power from the cells between 1 – 1.43 side areas.

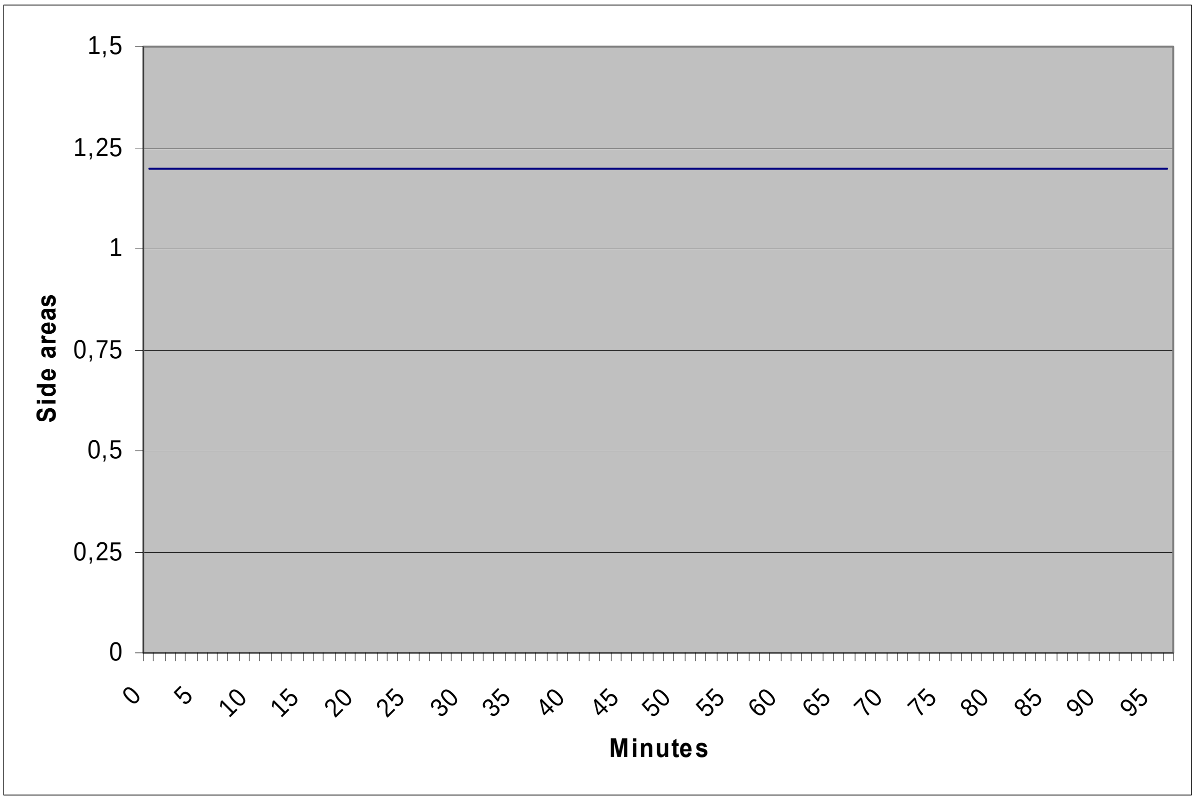


Figure 108: Shows a drawing of energy available from solar cells in a 90º orbit

To simulate the transmitters and receivers there is two switches connected to them. One switch will pull the outputs high after 10 minutes, and the other one is pulling them low again after 11 more minutes. This is to simulate the time that the satellite will have radio contact with the ground. The DC/DC converter to the magnetometer and the magnetic coils is controlled from the PMU, but when the magnetometer is activated, it will internally switch on and off the magnetic coils. The magnetic coils will be turned on for about 50% of the time the magnetometer is on. This is made by taking the output from a sinus wave that is connected to the timer. When the output is positive an the magnetometer is turned on, then the magnetic coils is also turn on, and when the output from the sin wave is negative or the magnetometer is turned off, the coils is turned off. To decide when the magnetometer is turned on, the third analogue input is connected to the ADCS DC/DC converter.
To get the right output voltage from the OP, the output is connected to an analogue input on dSpace where the output voltage is measured. The output voltage is measured and the difference is integrated and added to the calculated voltage.

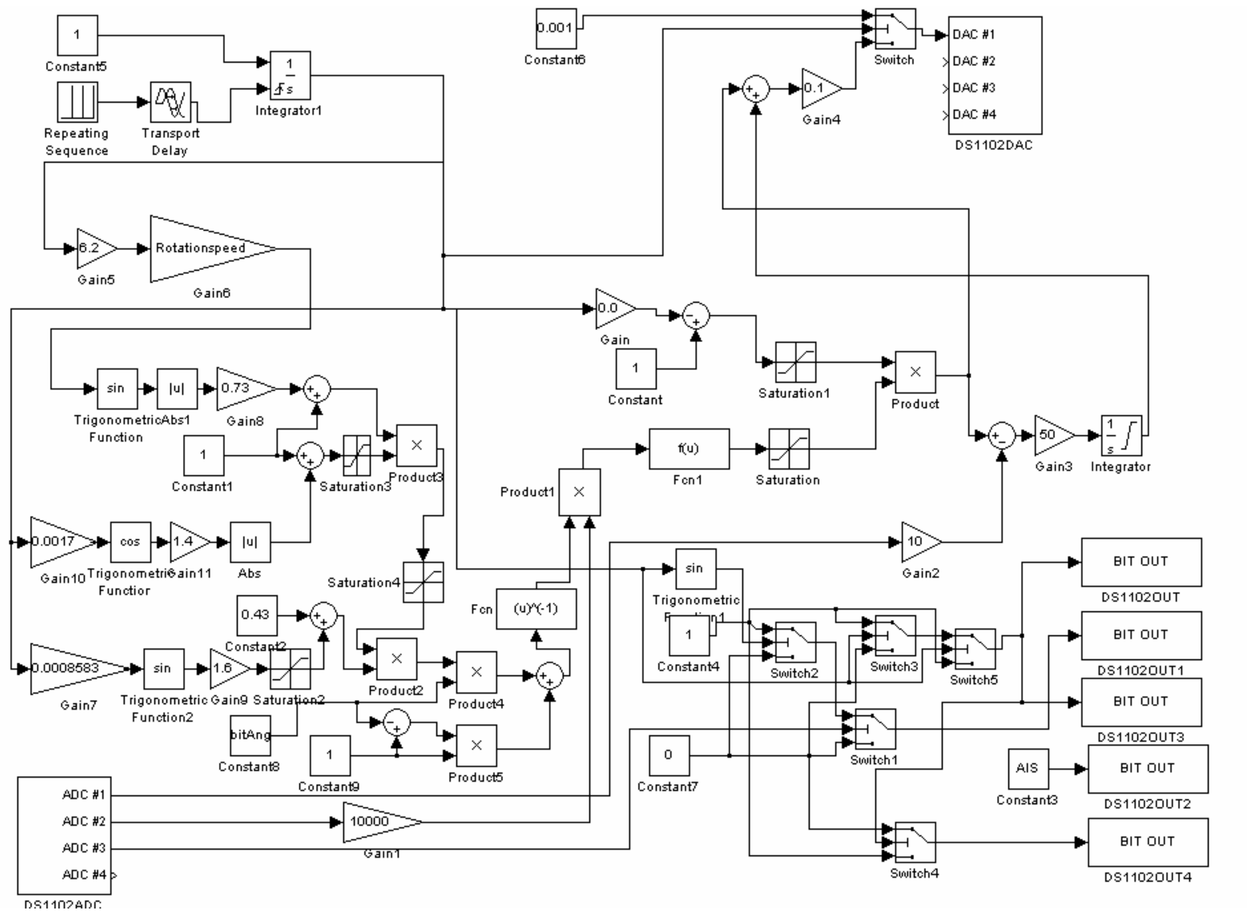


Figure 109: Block diagram of the simulator in Simulink

7.8.5 Using the simulator

To use this simulator the interface card has to be connected between the satellite and dSpace. The simulator is controlled from Controldesk in which all parameters are set. There are three scrollbars that control the rotation speed, orbit angle and the time in which the satellite is in the sun. There is also a bottom in controldesk that controls the AIS. The rotation is set between 0 and 1 turn per second. The scrollbar for orbit angle is for setting the orbit between worst case (1) and best case (0). For setting the time of which the satellite in the sun in each orbit, the third scrollbar is used. By setting this between 3660 (worst case) and 5760 (best case, no shadow) the different orbits can be simulated. The AIS can only be turned on or off, the light (marked AIS) is for checking for in which state the AIS is. The graph is showing the output current and the output voltage.

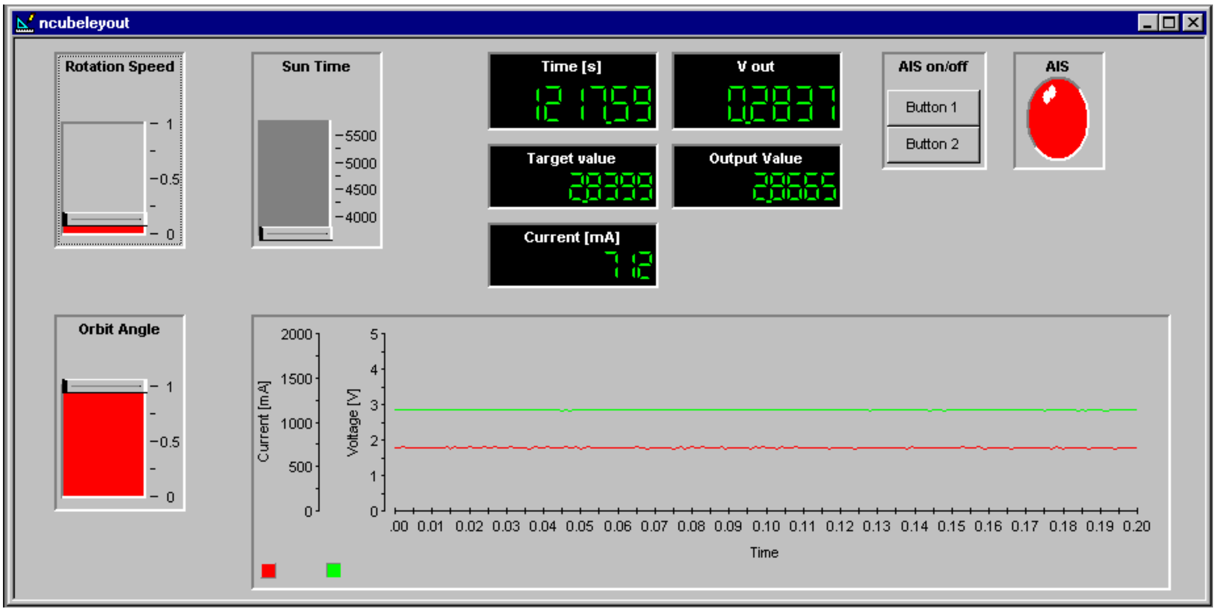


Figure 110: Shows the control table from Controldesk

7.8.6 Results

The critical part of the satellite is the charging of the batteries. If the battery energy decreases from orbit to orbit or if the solar cells deliver less power then the system consume there will be a major problem. By measuring the total of power going in and out from the batteries, its possible ensure that the batteries are charged and therefore the total power delivered will grater than the power used. By measuring the current to the batteries in worst case orbits, with AIS turned on, calculations of the power can be done.

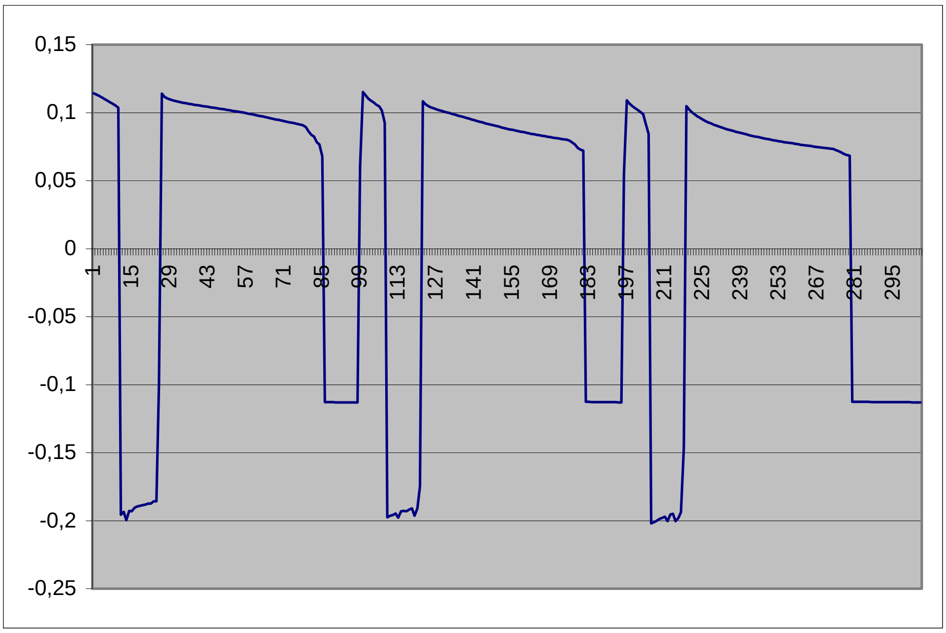


Figure 111: Current to the batteries in a 16 min shadow orbit.

By integrating the current, it's easier to see which way the power flow.

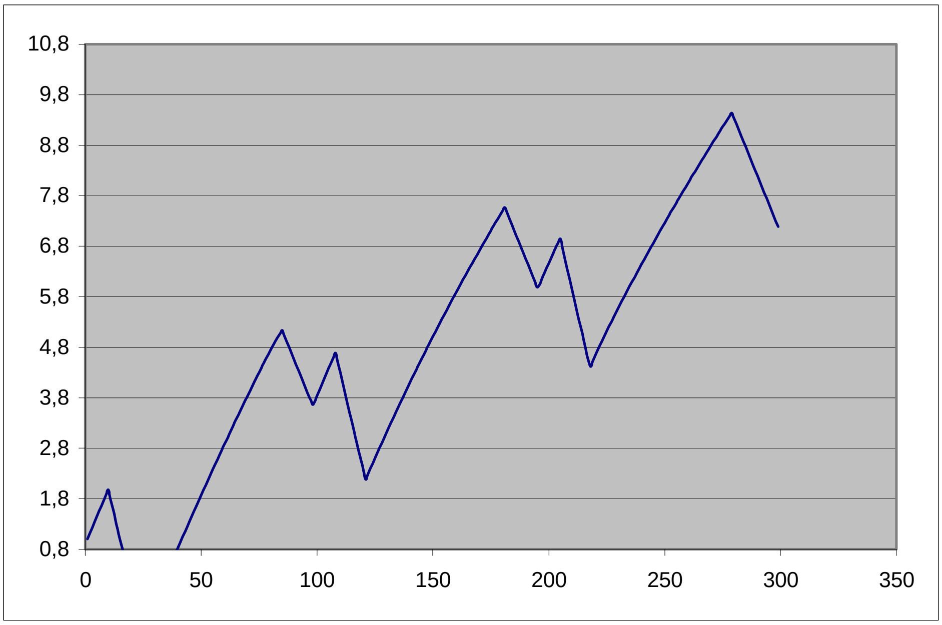


Figure 112: Integration of the current to the batteries in a 16 min shadow orbit

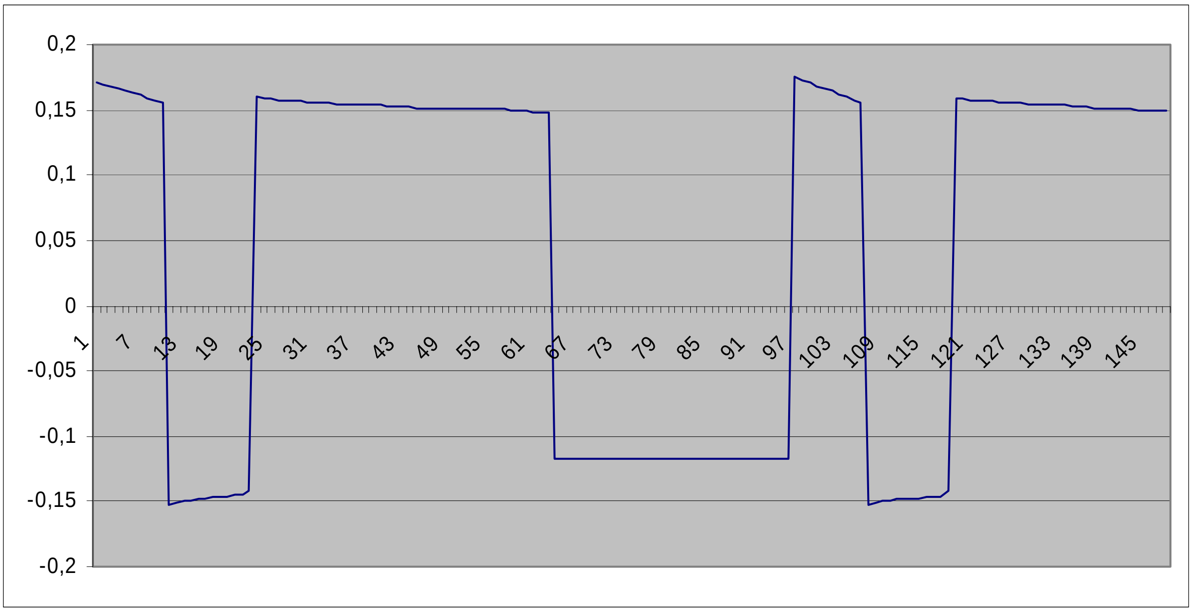


Figure 113: Current to the batteries in a 35 min shadow orbit with charged batteries.

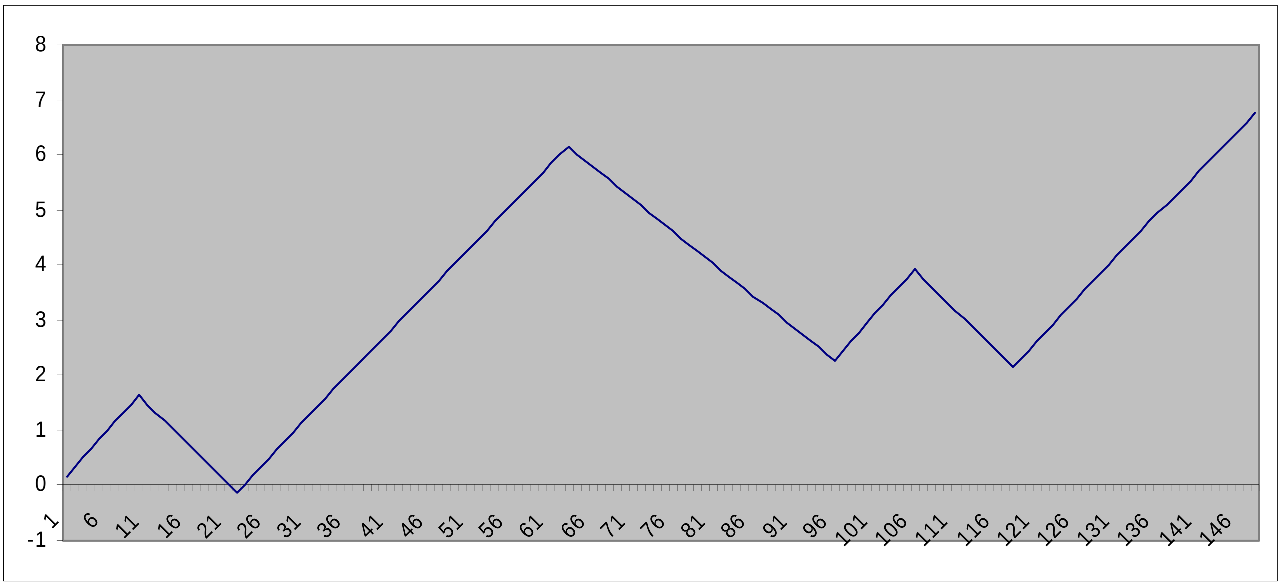


Figure 114: Integration of the current to the batteries in a 35 min shadow orbit with charged batteries.

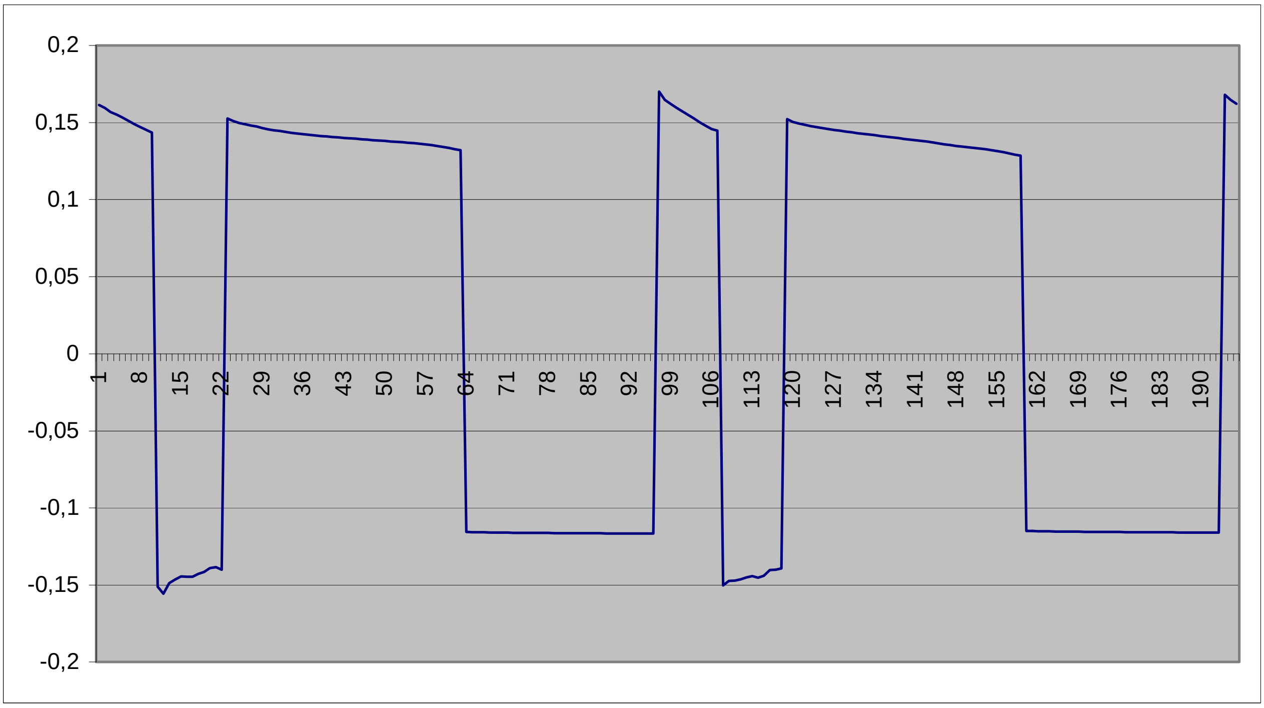


Figure 115: Current to the batteries in a 35 min shadow orbit with discharged batteries.

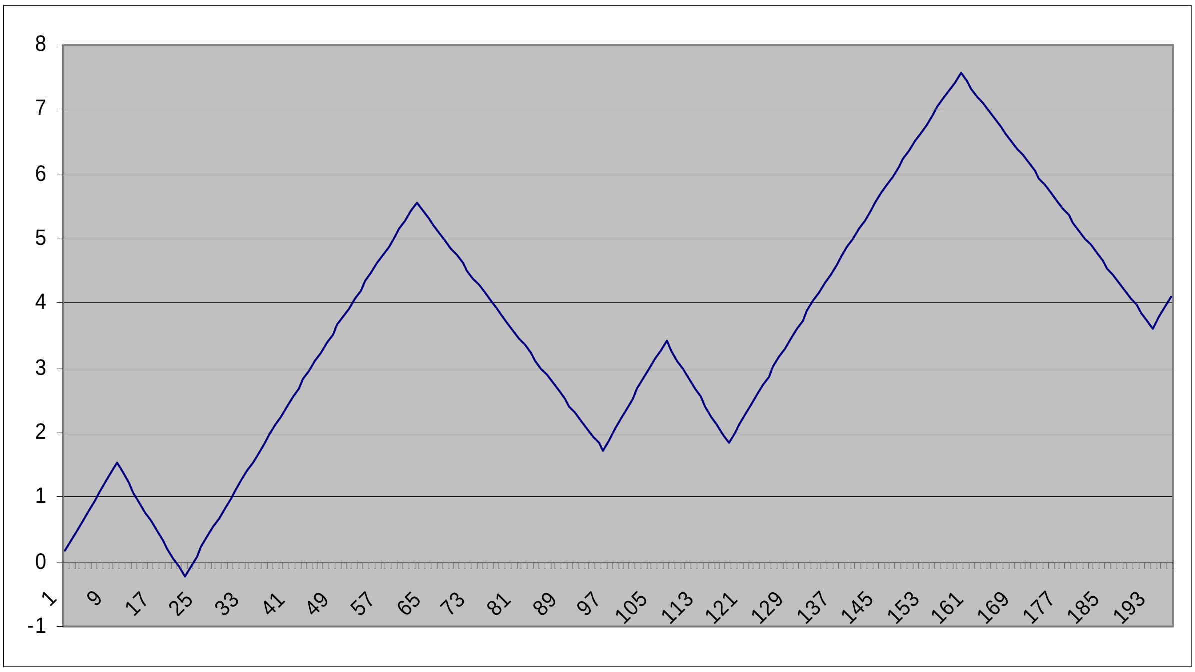


Figure 116:Integration of the current to the batteries in a 35 min shadow orbit with discharged batteries.

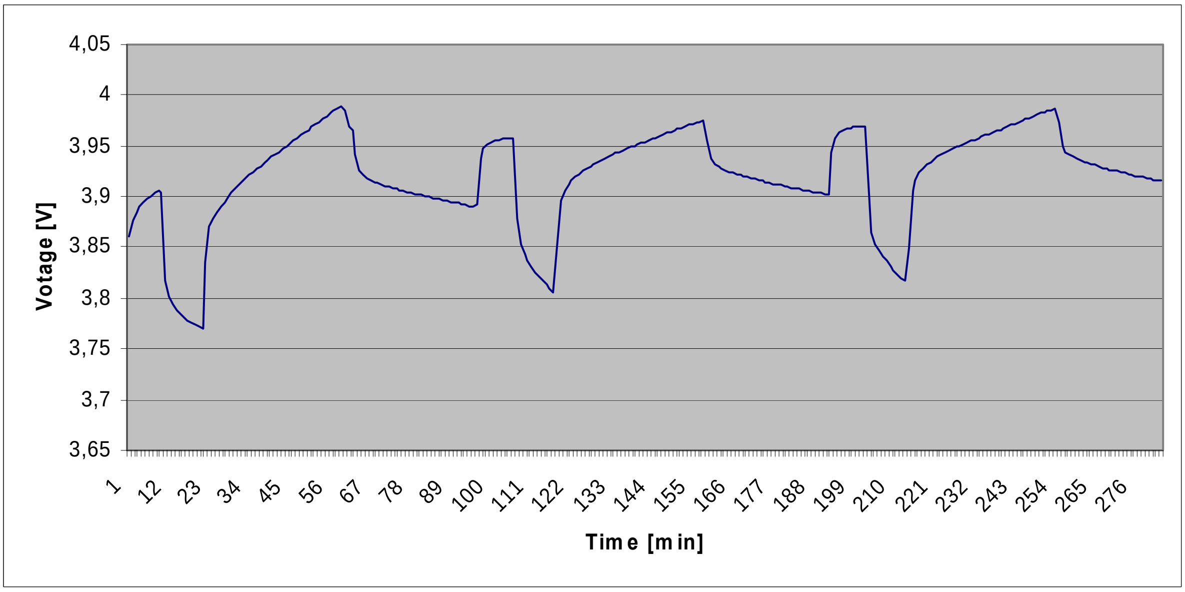


Figure 117: Battery voltage for 3 orbits

8 Developing the power supply system

There have been many stages in the development process. The work began for about one year ago, since that time many designs has been considered and tested. In this chapter the process and some the previous designs is described.

8.1 First stage, fall 2002

The first stage in this project was to brainstorm, finding technical solutions. There where several groups on each subsystem and therefore many reposts. Our contribution consisted of three different designs, some discussions regarding solar cells and choice of batteries. Below is the essence of the work.

8.1.1 Solar cells

Much work was spent contacting different manufactures regarding price and performance on solar cells. The conclusion of this research is that it's very expensive to use high performance cells. They are only delivered in standard sizes, which make it hard cover the entire surface. This makes the difference smaller between expensive and sheep custom made cells. Below is a comparison between the cell types.

Energy from sun	1352	W/m2
Solar cell area/side	0,00538	m2
Eclipse	33	%
Area towards the sun	0,00761	
Solar cell efficiency	26,5	%
Power after the solar cell on average	1,82775	W
Power after the solar cell	2,72799	W

Figure 118: Calculation of triple junction solar cells

Energy from sun	1352	W/m2
Solar cell area/side	0,008	m2
Eclipse	33	%
Area towards the sun	0,01131	
Solar cell efficiency	18	%
Power after the solar cell on average	1,84471	W
Power after the solar cell	2,7533	W

Figure 119: Calculation of single junction solar cells

There is very little difference between the two types of cells.

8.1.2 DC/DC converters

Information about the DC/DC converters was found in the datasheets from the manufactories websites. Below are a comparison made.

Company	Microchip	Microchip	Maxim	Maxim	Maxim	Maxim	Maxim	Maxim	
Type:	**TC110**	**TC115**	**MAX 608**	**MAX 170**	**MAX 170**	**MAX 710**	**MAX1672**	**MAX 770**	
Quiescent Current	50 - 280	80 -135	85 - 120	35 - 110	65 - 120	100 -140	85 - 125	85 - 110	µA
Shutdown Current	0,5	0,5	2	3	1	0,2	0,1	5	µA
Max. Output current	300	140	1500	800	1500	500	300	1000	mA**
Efficiency	84	85	85	<96	<95	85	85	90	%
Temp. Range	-40 - +85	-40 - +85	-40 - +85	-40 - +85	-40 - +85	-40 - +85	-40 - +85	-55 - +125	°C
Output Voltage	3 / 3,3 / 5	3 / 3,3 / 5	5*	2,5 - 5,5	2,5 - 5,5	2,7 - 5,5	1,25 - 5,5	2 - 16,5	Volt
Input Voltage	2 - 10	0,9 - 10	1,8 - 16,5	0,7 - 5,5	0,7 - 5,5	1,8 - 11	1,8 - 11	2 - 16,5	Volt
Numer of Pins	5	5	8	16	16	16	16	8	Pins
Number of comp.	7	4	7	7	7	6	9	7	Pcs
Step up / Step down	Yes / No	Yes / No	Yes / No	Yes / No	Yes / No	Yes / Yes	Yes / Yes	Yes / Yes	

*Adjustible with extra components
** Depending on the input voltage

Figure 120: Comparison of different DC/DC converters. Highlighted areas are positive qualities.

8.1.3 Comparison of microcontrollers

Company	ATMEL	MicroChip	MicroChip	Texas	
Type:	AT90S8535	PIC18F1220	18F4320	MSP430	
Required voltage:	2,7 - 6	2 - 5,5	2 - 5,5	1,8 - 3,6	Volt
Current at 32 kHz	2000*	?	28**	14*	µA
Numbers of I/O	32	16	34	48	Pieces
Numbers of AD	8	7	13	8	Pieces
Accuracy (AD)	10	10	10	12	Bit
Temperature range	-40 - +85	-55 - +125	-55 - +125	-40 - +85	°C
RAM	512	256	512	256	Byte
ROM	8	8	8	8	Kbyte
EEPROM	512	256	256	256	Byte
Communication	UART SPI	USART	SPI, I^2C UART, PSP	USART UART, SPI	Type

* Approximated values
** Is not available before July 2002, the value is from the older circuit and therefore should be lower in the new circuit.

Figure 121: Comparison of the different microcontrollers. Highlighted areas are positive qualities.

8.2 Second stage, autumn 2002

The second stage of the development process has included building and testing the DC/DC converters, batteries and the solar cells. Free samples of batteries and DC/DC converters where ordered. Polycrystalline single junction solar cells where supplied by Oslo University. The tests at this stage where very time consuming due to the fact that new programs for developing PCB´s had to be learned.

8.2.1 Charging

Different charging circuits where tested. Below is a part of the report: *nCube – Norwegian student satellite, Power supply, HIN*

[13]

Two different battery chargers from maxim, MAX1736 & MAX1879 where tested. They both behave very similar and they are both pulse chargers. They charge the battery by using pulse charging and time limit.

At the beginning, when the battery is empty the charger will have a high "turn on" duty cycle which decreases when the battery get charged. They haven't any current regulation of its own, so they have to be connected to a current limited DC source. In the satellite this won't be any problem because the solar cells have a natural current limit. When charger is turned on and the battery voltage is between 2.5 and 4.0 volt, the "turn on" duty cycle will be 100% and the battery will be charged at a maximum current provided by the DC source. When the battery voltage increases the "turn on" duty cycle will decrease. When the duty cycle on the MAX1879 charger is 1/8 the battery has approximately 95% of full capacity.

This charger also has a charging timer that will turn of the charger when the charging timer expires (approximately 6.25 Hours). The charger will start again when the battery voltage gets below 4.0 volt. They both have a precharge mode that will be used if the battery has a voltage level below 2.5 volt. In the satellite the voltage level will be kept over 3.0 volt all the time so this function wont be necessary. The chargers have an efficiency of about 70-90 % depending on the charging current and charging mode.

Instead of using a charger a DC/DC-converter might be used with an output voltage of 4.2 volt. This will ensure that the battery won't be charged with a higher voltage than 4.2 volt. The current is also limited by the solar cells so we might not have to use any charger at all. In such a case a zener diode could be used to ensure that the charging voltage never exceed 4.2 volt.

As seen, one of the options at this time was to use a DC/DC converter instead of a charger. This is the option that is used in the power supply system.

8.2.2 DC/DC converters

There where many DC/DC converters assembled and tested. Some converters where very poor and could never be considered to be used on the satellite. A big problem in the development process was that the subsystem groups couldn't decide what voltage levels to use. This resulted in a lot of testing which weren't necessary to do in the end. Below are test results of some of the converters that where considered.

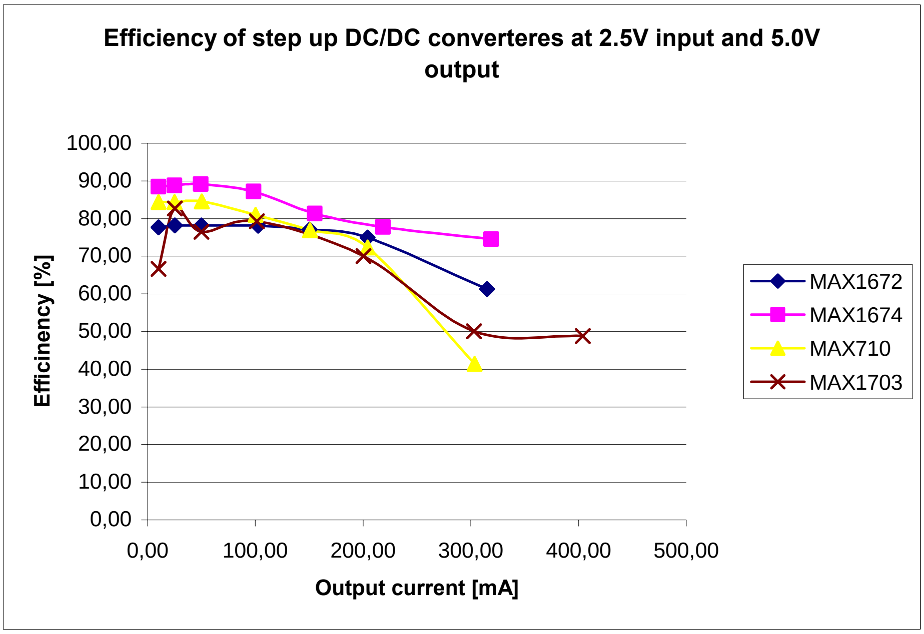


Figure 122: Test results of DC/DC converters. Complete results is in appendix.

8.3 Prototype implementation

Between the second stages and the prototype implementation tons of PCB layouts and PCBs was made and tested. The power demands where determined and the finale choice of DC/DC was made.

Late in march this year (2003) there was a big point on or work flow diagram. There where a gathering at NTNU, Trondheim called prototype implementation. The goal on this gathering was to test all the subsystems on the backplane. All the subsystems should be assembled and tested. The DC/DC converters should be connected to the respectively subsystems and be tested properly.

All the circuit boards where made in a relatively large size so that it would be easy to changes things around. The backplane on this meeting was measuring the size of an A4 paper and all the DC/DC converters where on separate PCBs. The PMU wasn't properly prepared so a complete test wasn't a possibility. But system integration and some proper communications test should give many answers on the continuing work.

Sadly there wasn't any other PCB available when the gathering started, so not many tests where made. The TNC was the only system available, but without the PMU properly prepared (in fact the routine controlling the I2C bus was the one that was missing) not many tests where made. It was possible to test the traces and control the I/O expander to switch on/off the enable pins on the DC/DC converters.

After the prototype implementation the main task was to crimp the system to the right size. The A4 PCB should be 80*80 mm, and the DC/DC converter should be implemented on a PCB that could be attached to the structure. The software should be written and tested properly and be ready for the finale test on Andøya (ARS) in May. This report is mainly documenting the work done between these to occasions.

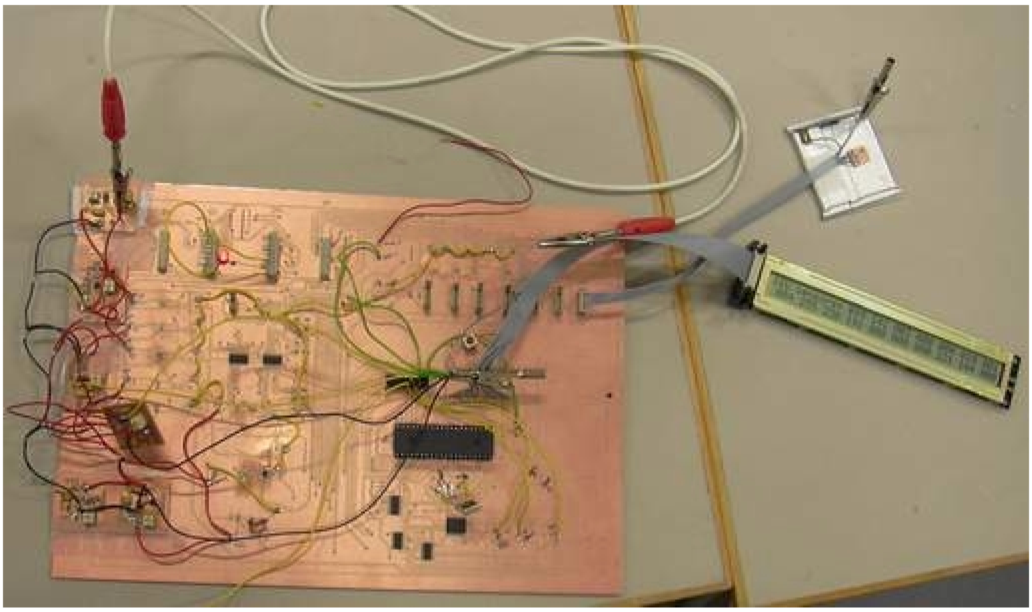


Figure 123: This ist the first layout of the backplane. The DC/DC converters are attached with tape on the left side. This PCB is the size of an A4 and is using DIL44 instead of the TQFP

8.4 Balloon Test

8.4.1 Goal

The balloon test took place at Andøya rakett skytefelt (ARS), where all the participants where available. The satellite should be put together without the structure. Several tests should be done regarding the function of the satellite. The satellite should be launched with a whether balloon.

The testing part of this gathering was assigned almost 4 days before the balloon test it self. But with the rather poor results from the prototype implementation at NTNU, Trondheim there was a lot of work to do. Many of the systems that should be on the satellite wasn't ready and a couple of alternatively solutions where made.

The system that was finished and should be onboard in the balloon test was: Power PCB/ Backplane, TNC and the S-band transmitter. The origin radio was exchanged with a radio produced by Kenwood, AIS receiver and ADCS systems where excluded.

As expected some problems occurred and the real integration tests weren't made before the day of the balloon launce. But before putting the system together it was possible to get some house keeping data through the TNC.

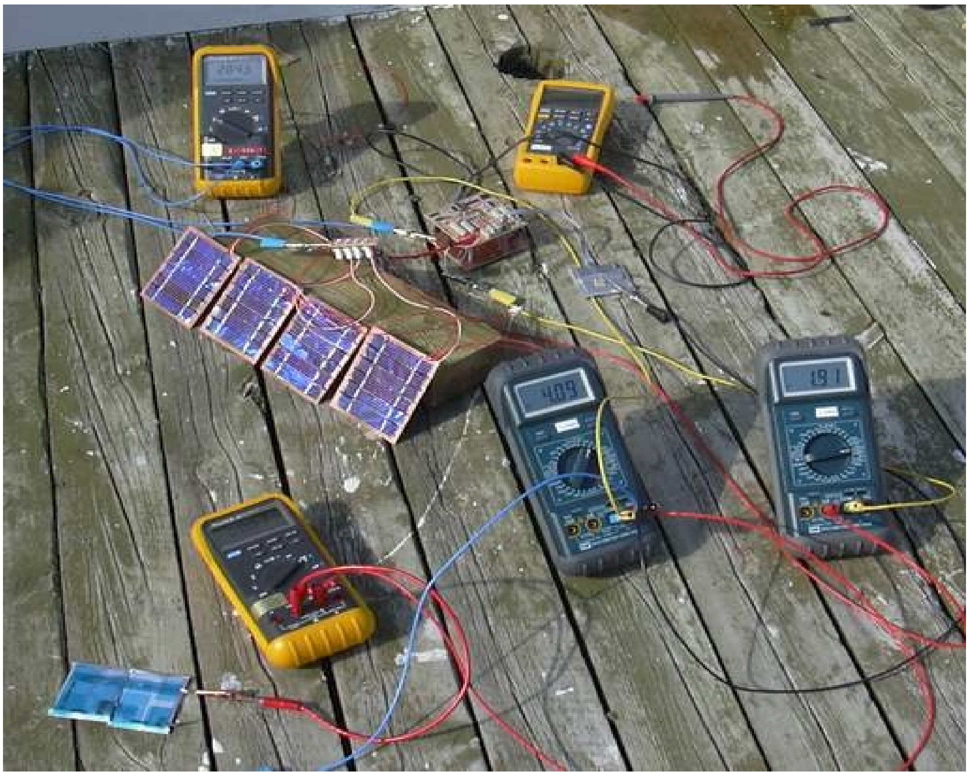


Figure 124: Here you can se the Power PCB/ backplane when the solar cells are attached and are charging the batteries.

8.4.2 Problems that occurred during the balloon test

When testing the system at ARS there where problems with the communication. This made it impossible to test the power management system properly. The main reason for the communication problem believes to be in the data selector switch. The switch that was attached on the backplane at the test was only a one way communication circuit. Therefore no data could be returned. After hard wiring the data selector there where a sporadic possibility of receiving a packet from the PMU which could be decode to the appropriate house keeping data. But these packages confirmed that all the sensors and the PMU soft ware (regarding house keeping data) functioned appropriate.

At this moment the status was "go", the balloon should be launched. When all of the systems where integrated, the box was sealed; the parachute and nearly the balloon where attached one last problem occurred. There was no signal coming from the Kenwood, and the ground station wasn't able to establish a connection with it. At this stage the test was called off. Some of the participants had a plane to catch and that was it.

8.4.3 The balloon

The balloon (measuring 2.5 m in diameter) should lift the satellite in a speed of 16 m/s to an altitude of 30 000 meters (the balloon then measuring approximately 9.2 m). Then a mechanism similar to the boom/ antenna release would burn of the balloon, and parachute will bring the satellite safe down to earth. The satellite was built in a water proof casket that also would protect the electronics from the cold (At an altitude of 30000 meters the temperature could get as low as -70 degrees Celsius). This box was equipped with a camera sending live picture from the trip. There was also a GPS tracking system to make recovery possible. The box was even marked with a promise of 1000Nkr finders fie.

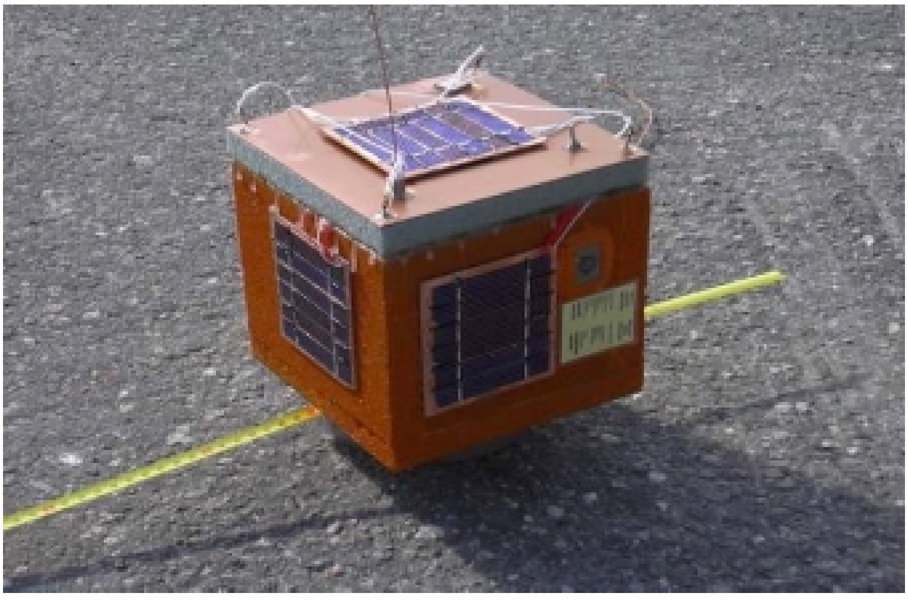


Figure 125: Here you can se the box that the satellite was implemented in. The solar cells one antenna, the camera and even the note explaining what it is and that it has a finder-fie.

9 Purposes for further developing

The problem with building an electrical system in a small a satellite is the demands on size, weight and space. The nCube satellite is bounded by 10*10*10 cm and 1kg. Nothing could exceed these limits because of the P-POD.

If the solar cell area could be multiplied by 10 and the battery capacity as well, there wouldn't be any power problems (if the subsystems where the same). The system could be built very simple with linear regulators and no "thoughts" on efficiency. But there is not much power available so high efficiency is of grate importance. Even heat could be a problem because of the surroundings. So when taking this in to consideration; an example further development is shown.

The different parts of the power management unit

Solar cells:
The solar cell configuration would be the same with 6 cells in series on each side. The DC/DC converter would convert from solar voltage to 6.0 V.

Charger:
A charger will be implemented. With the high voltage level from the solar cells, a charging circuit will provide a more efficient and reliable charging of the batteries. A charger will control the charging voltage and currents to get a most optimal charging without any risks.

All the subsystems will be connected on the same bus as batteries with the solar cells separated by the charger. The week link her will be the charging circuit; if it fails the solar cells could be blocked from the rest.

The subsystems:
If possible; most of them should be coupled directly on the battery bus; to avoid the use of semiconductors. This means that they must be able to use an unregulated power source that will vary between 3.1V and 4.2V. Each subsystem must be equipped with an enable pin with true shut-down.

DC/DC and DPS:
Supply every subsystem with two DC/DC converters in parallel to create redundancy and to make the stress on each converter smaller. If the same voltage divider is used on the converter the output voltage will be equal hence the load placed on each converter.

Theses developments aren't necessary to do, but could be a way for further work.

10 Measuring methods

When testing and collecting information about the different components used in the satellite, measurements where made in different ways.

10.1 Testing the DC/DC-converters

For testing efficiency, ripple and noise different instrument have been used. For testing the efficiency, 4 multi-metres, 2 for current and 2 for voltage measurement, have been used. A variable resistor has also been used as a variable load. As power source a battery or a DC power supply have been used. Batteries are to prefer because they have no output ripple, something DC power sources always have.

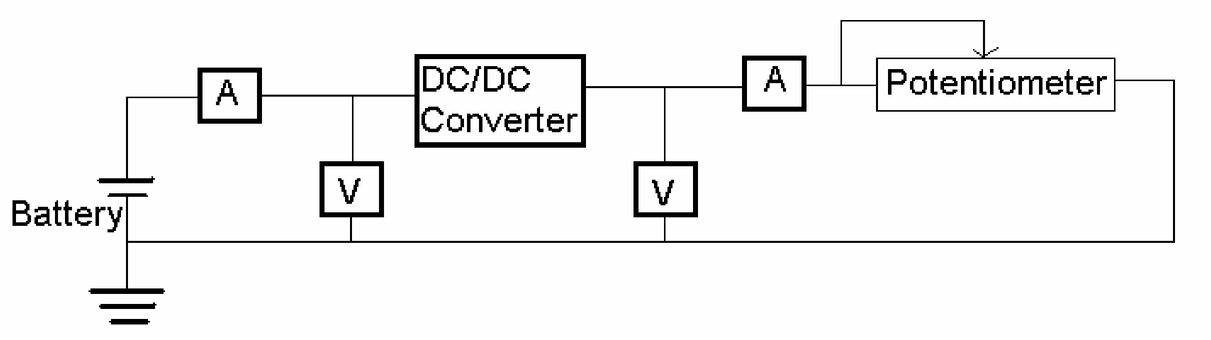


Figure 126: Method for testing DC/DC-Converters.

It's very important to connect the voltmeters between the DC/DC, that should be tested, and the current meters. This is because of the mayor energy looses in the current meters, to avoid this to affect the measurements. The connection has to be done as shown in the picture above.

All DC/DC converters that have been tested are tested with different loads between 0 and maximum specified current.

For testing ripple and noise a current meter, a variable resistor and a combined spectrum analyser/oscilloscope have been used. This is done for measuring the ripple and noise with different loads.

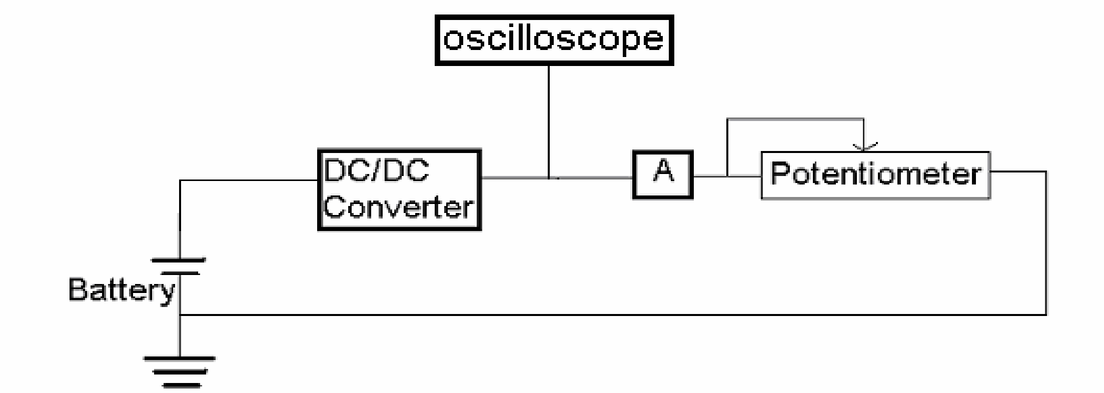


Figure 127: Method for testing the DC/DC converter with oscilloscope.

10.2 Testing the solar cells

To be able to build a mathematic model of the solar cells, measurements had to be done. For this purpose a 2000 Watt halogen light source, a voltmeter, a current meter and a variable resistor where used.
The halogen lamp was mounted with a distance of about 1.5 meter from the solar cells. Then the voltage and current meters where connected. The halogen lamp was turned on for a short time and the output voltage from the solar cells where noticed. The variable resistor where attached. The variable resistor was adjusted to maximum resistance, about 25 ohm. The halogen lamp turn's on and both the current and voltage values are noticed. Then the variable resistor is adjusted to increase the load and another measurement is done. This is done for several different loads and all results where noticed. By doing this the characteristic of the solar cells can be calculated.

The halogen lamp should only be turned on for a very short time under each measurement because the heat from the lamp affects the efficiency of the solar cells. It is important to have the same solar cell temperature on every measurement.

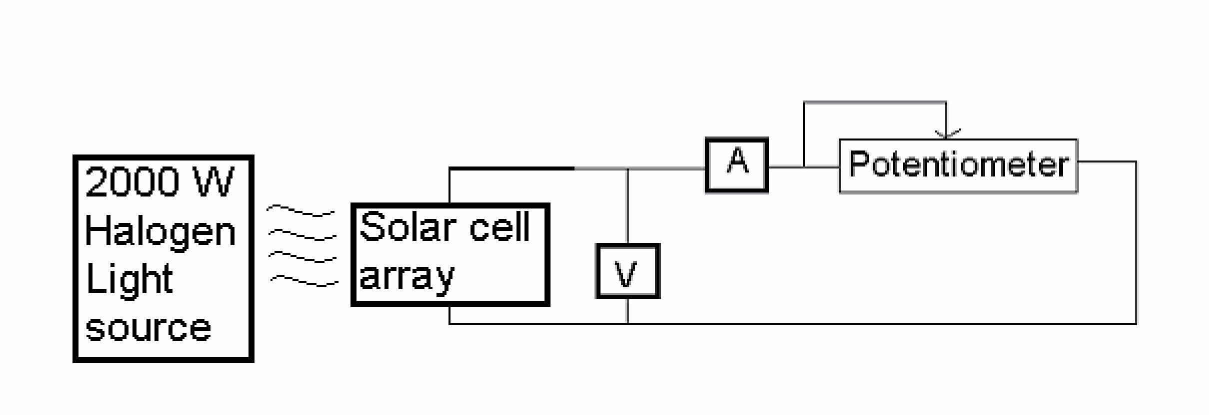


Figure 128: Method for testing the solar cells.

The solar cells used for these tests where polycrystalline single junction cells, not the monocrystalline type that should be used in the satellite. The halogen lamp has not the same light spectrum as the sun, and therefore it's not totally correct.

10.3 Testing the batteries

For testing the efficiency and capacity of the batteries a series of measurement have been made. To test the output capacity, the batteries where charged with 4.2 volt until the current dropped down to 0.05 CMA (75mA for a battery with the specified capacity of 1500mAh). The battery is then connected to a constant current load, a voltage meter and a current meter with data output.
The constant current load is built of a current limited DC power source and a resistor.

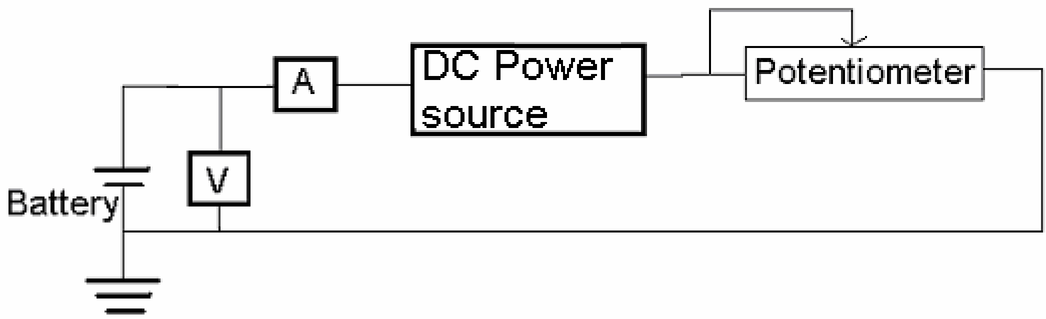


Figure 129: Method for testing the batteries.

By doing this, a load with an, independent of the output voltage, current is built. With only a resistor the current would drop as the output voltage drops and there will be problems calculating the capacity of the battery. When having a constant current it is easy to calculate the capacity of the battery my measuring the time and current. The measurements where done until the battery voltage drops down to 3 volt. The time and current where then multiplied to get the output capacity.

For measuring the efficiency of that battery, both the output and input energy has to be known. The output energy is already known but to measure the input energy, some more measurements had to be done. The input current and voltage is not constant so calculating the input energy is difficult to measure.
By logging the voltage and the current an approximated input energy can be calculated. Several test where made where either the current or voltage was logged. When having both these values, calculations of the efficiency can be done.

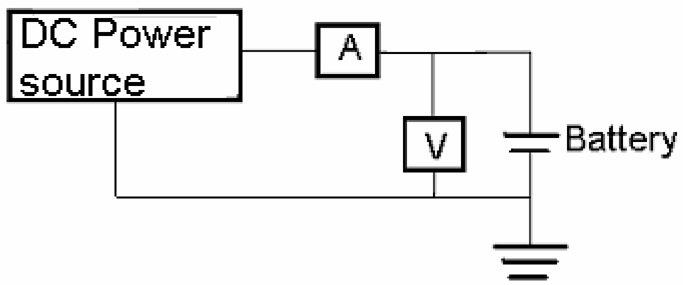


Figure 130: Method for testing the energy in the battery.

The current and voltage meters that where used are Fluke 89 multi-meters with an IR data output that connects to a PC with Fluke View Forms software for logging the values.

10.4 The satellite simulations

In the simulation with dSpace several internal measurements is done with dSpace own analogue inputs. One of these inputs is connected to a current measuring circuit MAX4372. Two others are connected directly to the point where the voltage should be measured. The current measurement to the battery is made with a Fluke 89 multi meter, with the log device attached. With this log device a series of samples can be done, with a selectable interval. In these tests it is set to 1 minute. By logging these values a graph and integrations can be done to se which way the energy flows.

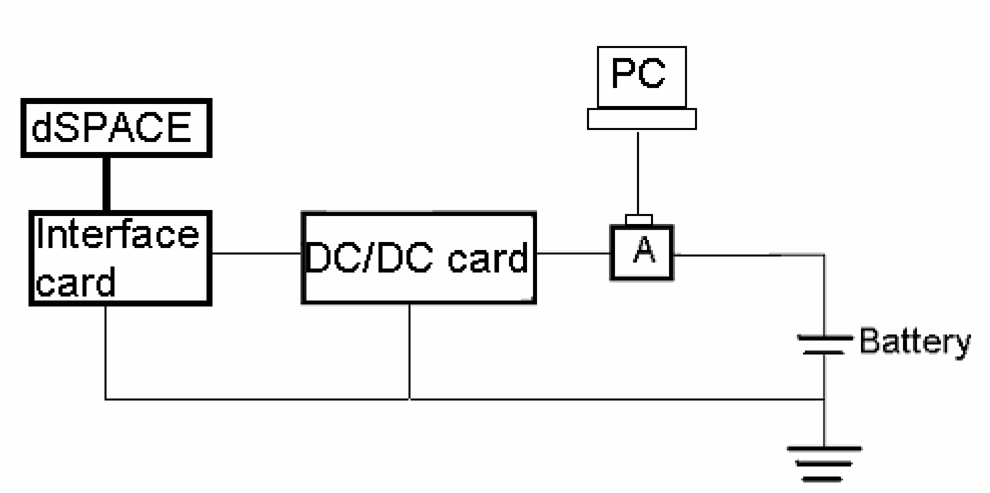
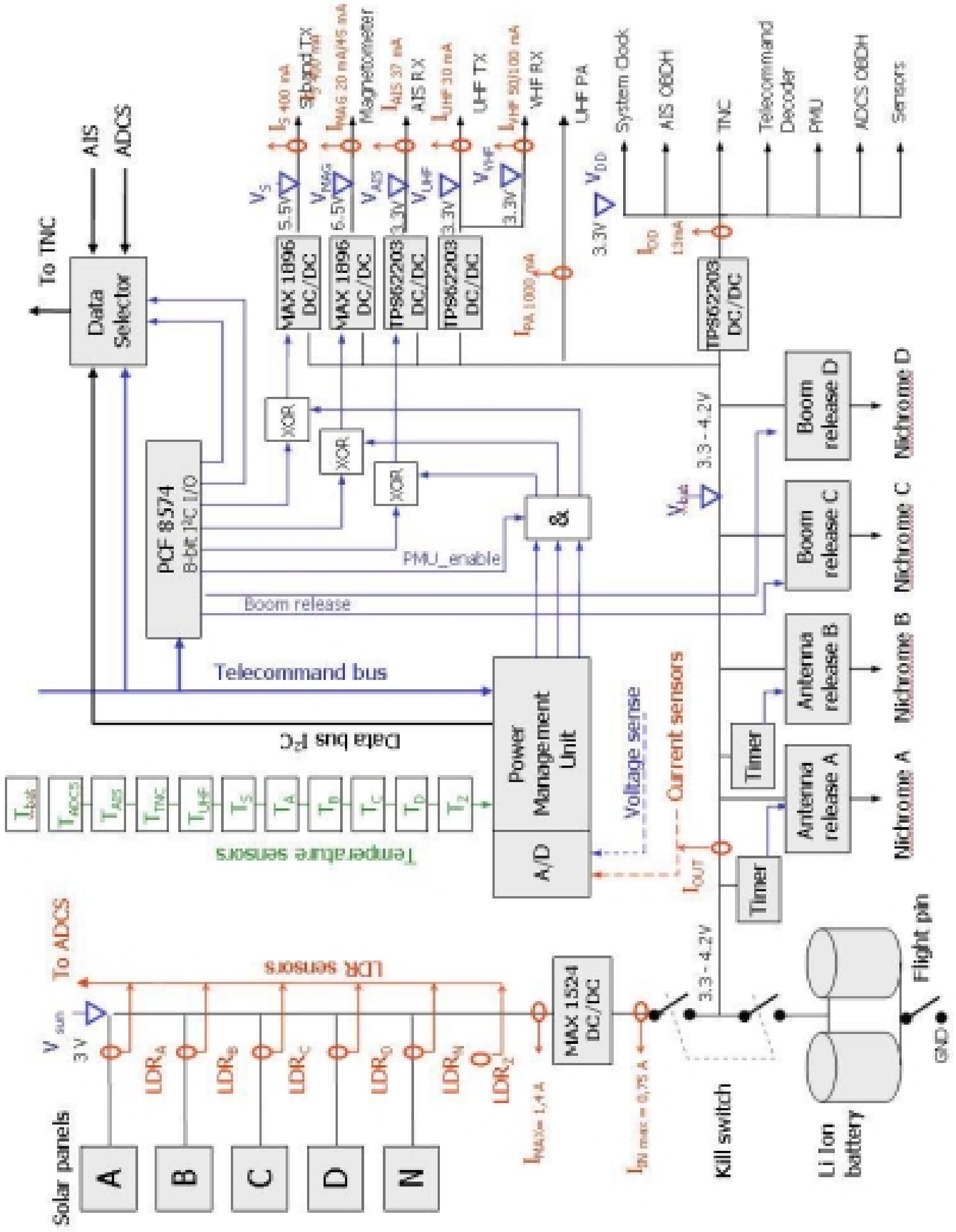


Figure131: Method for testing the satellite simulations.

11 Conclusions

During the nCube project the Power supply/power management system has been designed, produced and tested. The power supply system consists of different parts. There are 5 sides of the satellite covered with solar cells. A battery package, 29 sensors and a microprocessor that handles the housekeeping data is placed in the satellite. The complete system is designed as shown in the block schema below. The power supply PCB consists of two, double layer, PCBs; the Backplane and the Power PCB.



Electronics:
All the components used in the power supply system can handle the temperature range set in the task. All the components can handle vacuum. The batteries will receive special threat due to temperature and vacuum.

Backplane:
The backplane has been designed in the size 80*80 mm. All the connectors are in place and the traces connecting the subsystems are in place. The sensors, microcontroller and the other components that are a part of the power supply system are in place and working.

Power supply system:
As technical solution a distributed power system, based on DC/DC converters is chosen. This is made because it's very efficient way of handle power. The DC/DC converter makes it easy to set the voltage levels to the different sub systems.

Power management unit:
The power management unit has continuously been tested together with a LCD display and the "TNC emulator". The PMU collets information from the different sensors saves it and sends the data on request. It also turns off systems if some values are out of its limits. It can also turn the systems back on if such a commando is received and the failure disappeared.

DC/DC converter:
There are three different types of DC/DC converters applied on the satellite. Tests have been made regarding ripple on the output voltage, start up times and general characteristics.

One step down converter (TPS62203) used to all the systems requiring 3.3V. This DC/DC converter has efficiency up to 95 %. The converter is working with a good margin of its maximum of output currents.

There is one converter (MAX1896), with two different configurations. One supplying 6.5V/60mA, the efficiency is over 90%, it's working well with a margin of the maximum of out put currents. The other is supplying 5.5V/390mA. The efficiency is about 84%. The converter is working with a margin of the maximum of output currents.

The third converter is used as a boost converter (MAX1524). It's working with an efficiency of about 75% and is working with a good margin of the maximum of currents.

The DC/DC converters necessary are equipped with a thru shut down pin.

Battery:
The battery on board the satellite is chosen to be Li-ion batteries due to its extremely low weight, small size and good capacity. The battery has turned out to be stable and easy to handle.

Solar cells:
The solar cell used on the satellite is polycrystalline. These are relatively poor compared with the newest technology. But since the polycrystalline could be custom made (instead of

standard sizes) the difference in power is small. The efficiency in these cells is approximately 18%.

To be able to charge the Li-ion battery, a charging voltage of 4.2V is necessary. To be able to make the charging as efficient as possible, the range between solar cell voltage and charging voltage should be minimized. Therefore 6 cells/3.0V pr side was chosen.

Redundancy:
Redundancy has been implemented on the most crucial part of the satellite. Because of the limited space available redundancy in some areas had to be sacrificed.

Reliability:
Reliability has been considered during the developing of the power supply system. The components used have been properly tested by the manufacturers. All “power components” are placed on a separate board using a proper architecture with a ground plane separating them from the other components. This has resulted in a reliable and efficient distributed power system.

Sensitivity analysis:
The results from the Monte Carlo and worst case analyses showed that 10% tolerances on the components are sufficient. The output voltage varied with a few percent when the program (PSpice) performed the different tests.

Simulation:
From the results in the simulation it can be shown that even in a worst case orbit with all electronic turned on for its maximum normal time, there would be no problems in keeping the batteries charged. But there are many unknown factors that can’t be tested on earth. One of those is how efficient the solar cell really is in space. Another factor is how well the stabilization systems will work, and how this will affect the energy from the cells. The temperature on the cells is also an important factor that can’t be tested property on earth.

12 Sources

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