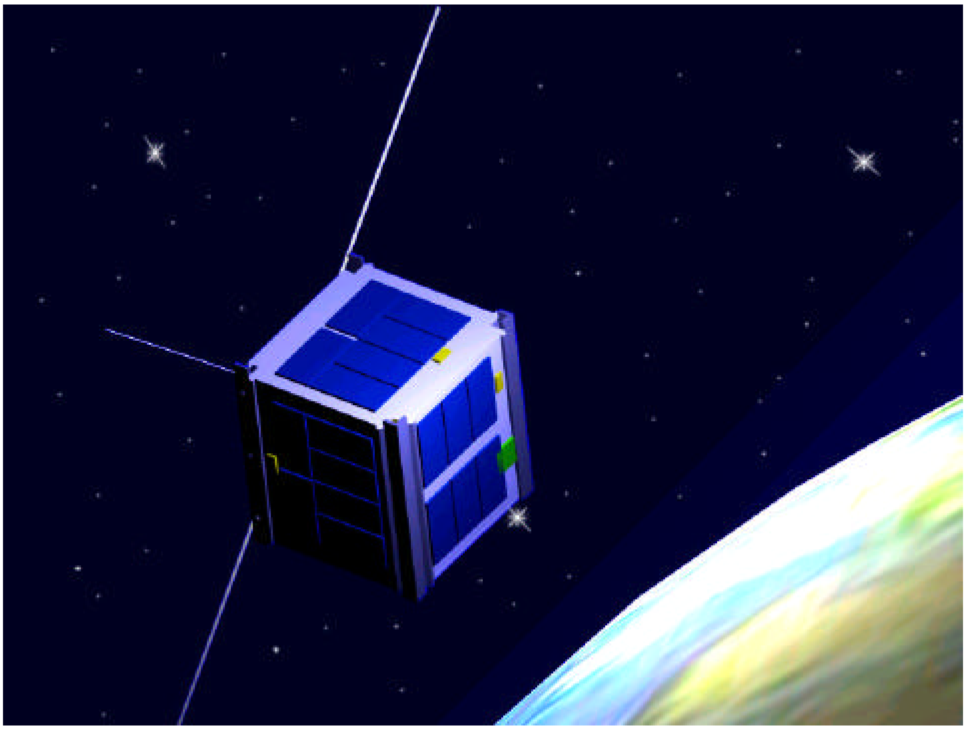
Mid-curriculum / Special Course at Eltek, DTU:

Design of a Power Supply System for DTUsat



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0. Abstract

This paper is the result of a combined mid-curriculum / special course project carried out at Eltek at the Technical University of Denmark. It is about the design of a power supply for the first Danish student satellite, DTUsat. The paper describes the choice of solar cells, batteries and converter topologies considered for the design. This is based on a discussion and feasibility study of the power budget. Furthermore space related issues, especially radiation, is studied. As the construction of the power supply is not yet complete, future plans of the project are described.

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1. Introduction

1.1 Cubesat - A Foundation for a Student Satellite

Students and professors at Stanford University, California, and California Polytechnic State University, have been designing student satellites for quite some time. One thing the projects lacked was the actual launch of the satellites into space. This was due to several reasons, one being the price exceeding several hundred thousand USD, the other the long delays from ordering a launch to the actual liftoff.

For the past couple of years students at Stanford have therefore been designing a new deployment mechanism that allows several tiny satellites to share one launch as a secondary or tertiary payload. This should effectively decrease the price of a launch, and if sufficiently many could be launched together the hope is that a university could afford to build and launch a satellite, say, every two years. Another goal will be fulfilled when the project becomes a success, since this will make it possible to launch such a bundle of satellite once or twice every year.

The result of their work is about to pay off. But the usual delays in the space industry is still showing. The launch scheduled for November 2001 has been delayed to May 2002, mainly because the primary payload of the mission experienced delays.

1.1.1 The Cubesat Design

The Cubesat foundation consists of small so-called picosatellites weighting no more than 1 kg, and having a size of 10 x 10 x 10 cm^3, see appendix A for the specification drawing. 3 such satellites will be put into a deployment mechanism called a P-POD (short for Poly Picosatellite Orbital Deployer), and finally 6 such P-PODs are installed as a secondary payload at a commercial launch.

When the satellites are being transported from the makers to the test and launch facilities it must be shut down. This is being handled by a so-called flight pin. When this pin is installed all power in the satellite is turned off, and when the pin is removed it may operate normally again.

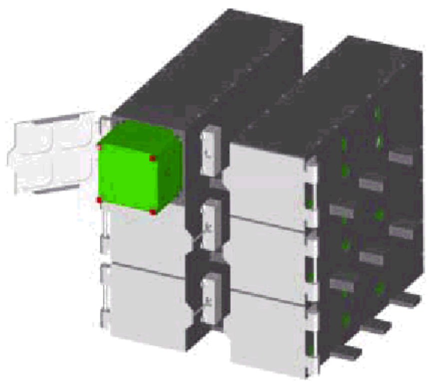


figure 1 - 6 P-PODs each containing 3 Cubesats

Because the satellites may not interfere with each other, the primary payload, and - more importantly, the launch vehicle - during the launch, they must be turned off. This is done by a kill switch that is mounted in the end of one of the rails, see appendix A for the specification drawing. As long as the satellite is in the P-POD the switch is depressed, and when the satellite is finally deployed the switch will activate and the satellite will begin to operate. The flight-pin can, and will, therefore be removed when the satellite has been properly installed in the P-POD. A schematic of these switches can be seen in figure 2.

Other issues exist when the satellite has just been deployed into space. Since 18 satellites are tumbling around relatively close to each other, it would not be wise if they all deployed their antennas at once when the satellites leaves the P-POD. Therefore a delay of several minutes must be respected. For the same reason the primary transmitter may not be activated until some additional

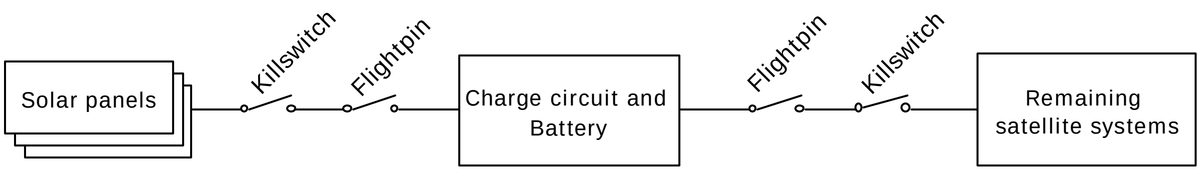


figure 2 - Overview of kill switches and flight pins

time has gone. Low power beacon transmitters may, though, be activated after deployment. These requirements along with several others concerning materials, static and dynamic g-load requirements, and temperature intervals are described in [BT01]. The time of the delays have not been exactly specified in the documents we've seen.

1.2 DTUsat - A Danish Student Satellite

In the spring 2001 some students at DTU saw the possibilities in the Cubesat project, and initiated a project of designing a Danish student satellite in cooperation with the Danish space industry and the Danish Space Research Institute (DSRI) who had already had great success by their first satellite named Ørsted, and are currently designing their second called Rømer.

The mission of DTUsat has been defined to be two-fold, namely to take pictures of the earth, and to deploy a tether that allows us to change the orbit. The latter payload is highly scientific and involves a high risk. NASA and ESA have tried a similar experiment and both have failed. The idea is to dispose of the satellite by lowering the orbit, when it's mission has succeeded. In the end it will burn up when reentering the earth's atmosphere. This will prevent a lot of garbage Cubesat's to float around in space in a couple of years when a lot of them will have been deployed.

In order to break the project down into feasible subprojects some working groups have been defined. These are:

SEG	System Engineering Group, handles interface discussions, monitors progress and other interdisciplinary problems. This group consists of one member from each of the following groups:
MEG	Mechanical Group, designs and builds the mechanical structure of the satellite
PWR	Power Group, designs the power supply described in this paper
OBC	On Board Computer Group, designs the computer on the satellite that handles everything from monitoring the satellite's systems to communication between the satellite and the ground station
OBS	On Board Software Group, designs the software that is executed on the OBC
BOT	Bootstrap Group, designs the software that initializes the OBC
ACS	Attitude Control System Group, designs the attitude control system that prevents the satellite from tumbling. This increases the efficiency of the antenna and the power gained from the solar cells
P-CAM	Camera Payload Group, designs the camera that takes pictures of the earth
P-THR	Tether Payload Group, designs the tether payload
RDO	Radio Group, designs the radio on board the satellite
ANT	Antenna Group, designs the antennas
COP	Communication Protocol Group, designs the protocol that specifies the data transmitted between the satellite and the earth
GSS	Ground Station Software Group, designs the software that controls communication from the ground, including monitoring software and software that is made public on the website for promotion

1.2.1 The Goals of DTUsat

The overall DTUsat project has the following goals:

A. Pre launch:

1. That all students gain some technical knowledge about space applications, and learn to work together in a large team
2. To finish and document all the modules, in order to allow others, including future DTUsatellite designers, to use our results

B. Post launch:

3. To receive a beacon signal, telling that the satellite is launched and that something works in space
4. To establish two-way communication with the satellite
5. To obtain three dimensional attitude control
6. To receive pictures of the earth from the camera
7. To deploy the tether
8. To change the orbit using the tether

1.3 Constraints

As mentioned in section 1.1.1 the Cubesat foundation sets up some constraints, the most important for us are:

- Size: 10x10x10 cm
- Mass: Max 1 kg
- Flight pin to turn off the satellite during transportation
- Kill switch to turn off the satellite during launch
- Antenna deployment delay
- Primary transmitter delay
- Optional: An RJ45 test plug that allows us to charge the batteries and communicate with the OBC when the satellite is in the P-POD

Furthermore the groups designing DTUsat have set up some additional constraints:

- Designed for 1 year of operation
- Based on solar cells and rechargeable batteries
- The solar cells are body mounted in order to simplify the design
- One side of the satellite is reserved for payloads, antennas etc.
- No galvanic isolation will be used
- The physical size of the PCB (printed circuit board) is 7x7 cm
- The size available for components of the PCB is 6x6 cm
- The maximum weight for the power supply subsystem has been set to:
  - Solar cells: 90 g
  - Batteries: 50 g
  - PCB: 100 g
- The maximum volume has been set to: 6 x 6 x 2 cm^3, excluding the battery

The complete weight budget for DTUsat can be seen in appendix C.

Finally it has been determined that:
- The expected temperature interval has been estimated to -40 to +80 °C
- The expected dose of radiation is 1 - 2 krad/year

Currently the orbit is unknown, but a polar low earth orbit (LEO) is highly possible (< 1000 km).

1.4 Overview of Possible Power Sources in Space

When a satellite is deployed into space it has only a few possible energy sources. Three of the most common are: Batteries, solar cells, and radioisotope thermal generators (RTGs).

When a satellite is in an orbit near the sun it can rely on irradiation from the sun all the time. This is also possible if the satellite is in a helios synchronous orbit around the earth (this means that the sun is always shining on the satellite). In the vicinity of the Earth the level of solar irradiation amounts to 135,0 mW/cm^2. Since the satellite might need power in order to get the solar panels ejected a so-called primary battery (non rechargeable battery) might be needed too. If the mission of the satellite is short in time, or the energy demand is minimal, it is, of course, possible to use these primary batteries as the only energy source.

For a longer mission where the satellite is orbiting the earth in any other orbit than helios synchronous orbit the earth will shade completely for the sun for some time. In the worst case it is about 35% of the orbit, as we will see in a later section. We will therefore need an energy storage when we don't get power from the sun, that is, unless the satellite doesn't need to operate when it is not in the sun. This storage is most often implemented by using a secondary battery (rechargeable battery).

The most common battery technologies used in space today are: NiCd and NiH_2. NiMh, which is often used in terrestrial applications is not very common in space. Batteries based on Lithium Ion technology is about to be used in space but as of now this technology is rarely used. One commonly known mission that featured Li-Ion technology was the Mars Lander 2001 [NA01].

It is obvious that when a combination of solar cells and secondary batteries is chosen the required power delivered from the solar cells must be sufficient to supply the satellite electronics with power *and* charge the batteries when the satellite is in the sun.

Finally the RTGs can be used if the satellite is traveling far away from the sun, for instance to one of the outer planets where the level of solar radiation is low. For example, the solar radiation reduces to about 58 mW/cm^2 in the Mars orbit, and to about 5 mW/cm^2 in Jupiter orbit. NASA's Pioneer [PI00] and Voyager [VO00] projects are some of the best known examples of spacecrafts implementing RTGs. It is obvious that this kind of power source is infeasible for our project, and we will therefore not spend more time on RTGs in this paper.

1.5 The Power Subsystem's Part in DTUsat

The different elements of the power subsystem includes energy sources, energy converters, energy storage, and control systems. The amount of electrical power required is dictated by the mission goals, e.g. antenna characteristics, data rate, and orbit.

From the above discussion it is evident that the basic configuration for a solar energy based system consists of:

- A solar cell array,
- Rechargeable secondary batteries, and
- A power conditioning and control system

Another important task is to protect the subsystems if a latch up occurs. This happens when a CMOS transistor is being hit by a high energy particle, because this causes it to short circuit. This means that excessive current is drawn and the chip will burn if the situation is ignored. Fortunately it is rather easy to correct. You simply have to turn off the power to the chip for a short time (ms) after which the circuit will operate correctly when turned on. More will be said about this in section 4.2.

It has also been considered to implement a priority control of the power usage allowing noncritical subsystems to be turned off when the power level is below some threshold in order to save the satellite. Another possibility is to turn off the entire satellite until a sufficient power level is reestablished.

Furthermore the power supply must monitor important currents and voltages that can be transmitted to the earth. This data is called housekeeping data and may be studied to see why parts of the system is not working correctly, or to predict when a system will stop working.

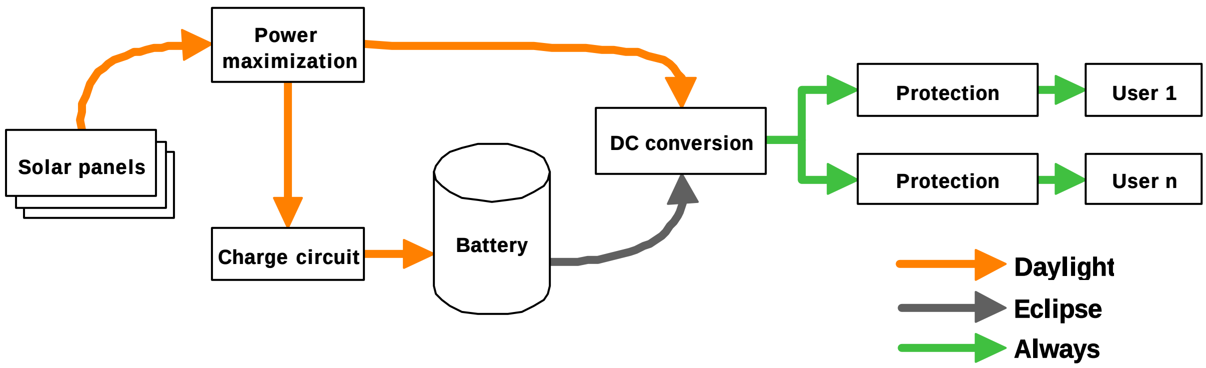


figure 3 - Architecture of the power system

In order to fulfill any of the post launch goals mentioned in section 1.2.1 the power supply *has* to work. This makes it obvious that the power supply is a vital part of the project. In order to increase the probability that this system works correctly we need to keep it simple. Some of the above mentioned ideas involves some rather complex solutions and therefore not all of these ideas will be implemented in the final system. On the other hand, by making the system simple and modular it should be straightforward for other groups to develop the system in the future, for instance by increasing the overall efficiency.

2. Solar Cells

We will begin this section with a short description of the physical characteristics of solar cells. For a more throughout explanation you can consult [MG82].

Solar cells are based on the photovoltaic effect that occurs when light is absorbed by a semiconductor. These photons contain various amounts of energy corresponding to the different wavelengths of the solar spectrum. Only photons with energies exceeding the band-gap energy of the cell can be absorbed by the cell. The band-gap energy is the minimum energy required to break a covalent bond and thus generate an electron-hole pair. If the band-gap is small a large current at a low voltage will be generated. If, on the other hand the band-gap is large a potential high voltage will be generated, but since the band-gap is large only very few photons will have a sufficiently high energy, and therefore the current will be low.

The photons emitted by the sun have energies between 1 eV and 3 eV. Research has shown that for standard cells an optimum band gap is about 1,5 eV. The conversion efficiency can be improved by stacking cells with different band-gaps on top of each other. This technique results in dual- and triple junction cells, which are commercially available today. An example of this is the Spectrolab dual and triple junction cells. The individual layers are shown in figure 4.

The cell is a sandwich construction of three layers, build on a Ge substrate. On the top and bottom of the cell are contacts for electrical connections. Furthermore the top has been covered by an anti-reflective coating in order to minimize the amount of sunlight reflected.

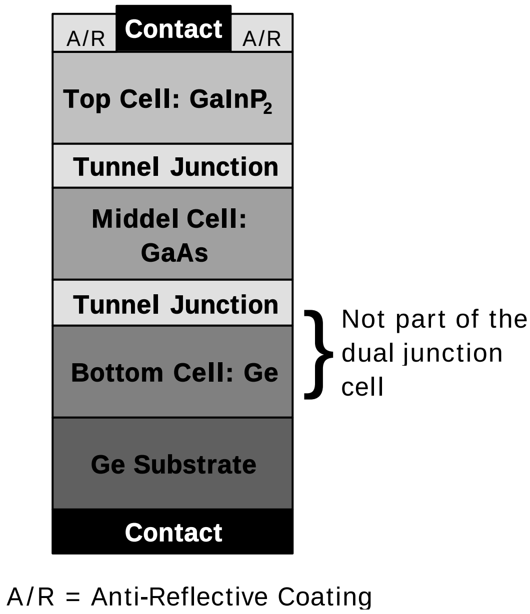


figure 4 - Outline of the Spectrolab dual and triple junction cells

The top cell removes the high-energy photons, but allows the longer wavelengths with a lower energy to travel to the second, and even third layer of cells. The top cell made by $GaInP_2$ converts the photons with a wavelength of 300 - 700 nm, while the middle cell made by GaAs converts the photons of 650 - 900 nm. Finally the bottom cell, made by Ge, converts the photons in the band 900 - 1600 nm. This third layer implies an increase in the overall efficiency of the triple layer cell with respect to the dual layer cell. The increase is, however, rather small: For some cells made by Emcore the dual junction cell delivers a conversion efficiency of 23,2% while the triple junction cell has an efficiency of 26%. A spectrum of the sensitivity of the individual layers for these cells can be seen in figure 5.

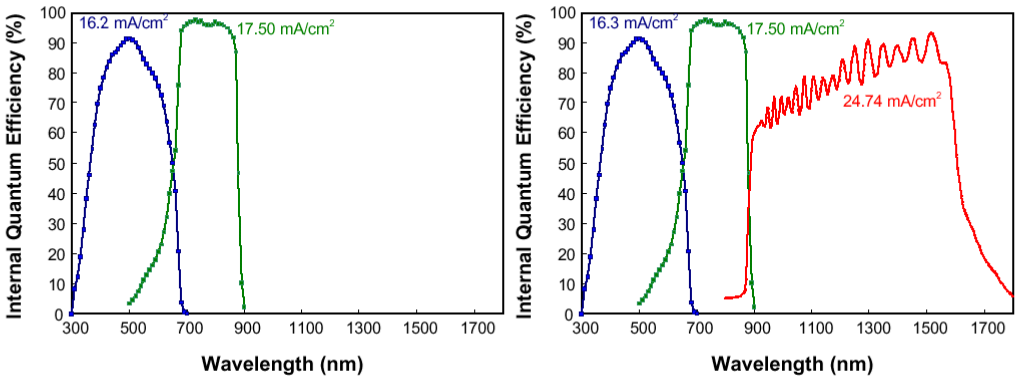


figure 5 - Internal Quantum Efficiency for Emcore's dual junction cells (left), and triple junction cells (right)

For the moment there are two important technologies for manufacturing solar cells. The most efficient one is the one described above based on GaAs, the other is based on Si, which is the material that forms the basis for most integrated circuits.

The tendency is that single layer GaAs cells are more efficient (typically about 18%) than traditional Si cells (typically about 16%) whereas Si cells are cheaper. Another important difference is that a single Si cell has a V_{oc} of about 0,6 V, and a dual and triple junction GaAs cell has a V_{oc} of 2,0 - 2,5 V.

2.1 I/V Relationship

The voltage and current drawn from a solar cell are unlineary dependent on each other. The I/V characteristic of some solar cells we've tested (see appendix E) is shown as a solid line in figure 6 along with the output power, calculated as $P = I \cdot U$ (dashed line). For the maximum efficiency of the cells it is therefore important to keep the voltage level around a certain point. This process is called maximum power point tracking.

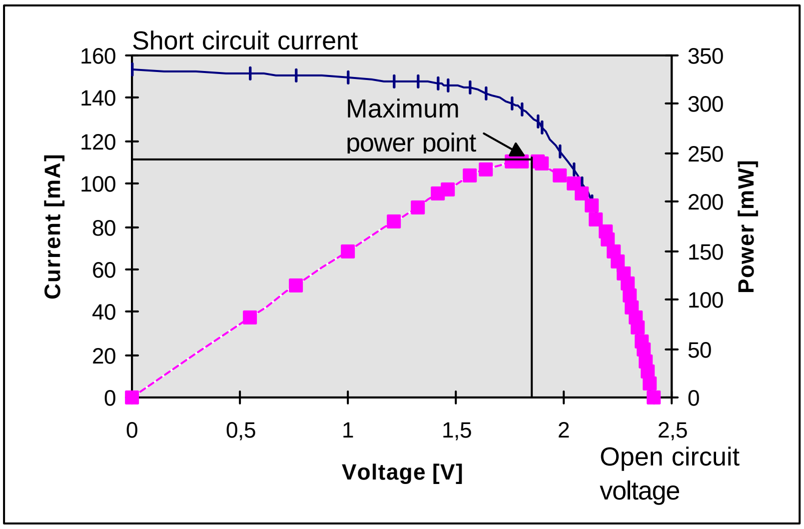


figure 6 - I/V characteristics of a solar cell

2.2 Temperature Dependencies

The conversion efficiency is somewhat dependent on the temperature. In general the voltage decreases slightly while the current rises by increasing temperature. An example from [WP78, p186] can be seen in figure 7 for a Si-cell from the 1970'es.

Since the change in current and voltage doesn't match we can find a temperature that gives a maximum power point with regards to the temperature. For this particular cell the point is at about -30°C. Notice that the efficiencies the manufactures state typically are measured at about 25°C.

The DTUsat is expected to be exposed to temperatures from -40°C when not illuminated, to +80°C when illuminated. It would, of course, be nice if the efficiency were highest when the satellite is illuminated, and therefore hot. On the other hand when the satellite is moving from night to day we'll need some extra energy to charge the battery. This extra energy is available because the temperature of the cells are cold.

It is also important to note that the maximum power point is dependent of the temperature. This further increases the complexity of a possible power point tracking system.

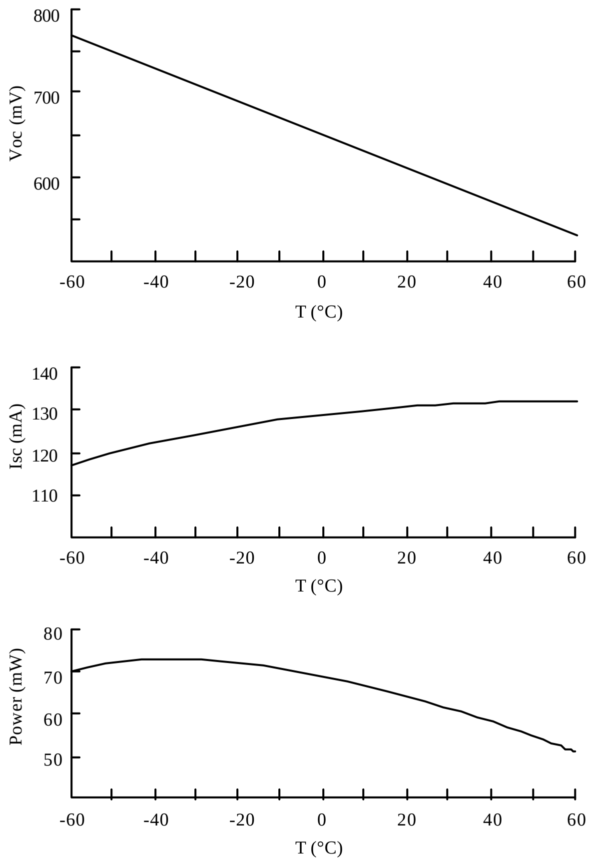


figure 7 - Temperature effect on I, U, and P

2.3 Connection of Cells

Because a single solar cell has a typical output voltage of 0,5 to 2,5 V, which is not sufficient to drive most electronic components, you most often connect several cells in series to create a *string* of cells that provides the proportional higher voltage. As illustrated on figure 8 a serial connection increases both the open circuit voltage V_{OC} and the voltage at the maximum power point (V_{MP}) proportional with the number of cells.

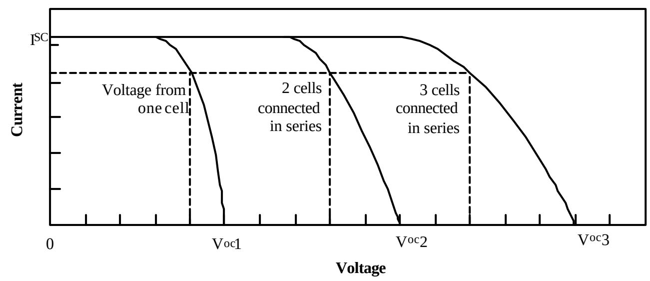


figure 8 - Serial connection of cells with the same level of illumination

In order to be able to draw a sufficiently high current you may need to connect some of these strings in parallel. This will increase the current that you can draw.

It is also possible to connect 2 or more cells in parallel to form a *submodule*, and then connect these in series to get the desired voltage. These configurations are shown in figure 10 along with the use of bypass diodes in each configuration.

It is evident that you will increase redundancy by placing several strings in parallel on each solar array, in this way, if a string malfunctions only part of the power provided will be lost.

2.4 Blocking Diodes

Two serious problems can arise by connecting a solar array. One occurs if part of the array is illuminated while other parts are shadowed for whatever reason. This will result in the shadowed cells acting as forward conduction rectifier diodes, causing power loss. Another problem occurs when one cell in an array breaks, resulting in a disconnection. We will deal with the latter problem in the next section.

An array is usually mounted on a flat surface. Consequently all the cells will be exposed to the same amount of sunlight. If two arrays are connected in parallel, one being illuminated, while the other is not, the current will flow from the illuminated array to the non-illuminated one. The latter will behave as series-connected rectifier diodes that are connected in the forward conduction mode. This will drain at least some of the power generated by the illuminated array. The problem can be fixed by using *blocking diodes* that are inserted between each array and the power bus such that they will conduct current from illuminated arrays but will block current flow into a non-illuminated array, as can be seen in the following figure:

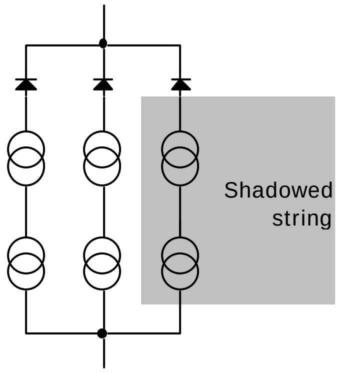


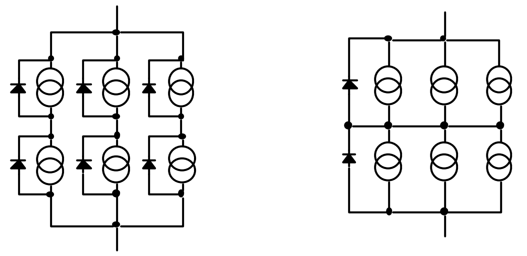
figure 9 - Use of blocking diodes

It is important to note, that when a body mounted configuration of solar cells is used blocking diodes are essential, since only part of the cells will be illuminated at any given time. The blocking diodes also solves the problem of the battery discharging through the solar cells when the satellite is completely shaded by the earth.

There is one drawback of using blocking diodes, namely the voltage drop across the diode. For a typical array of 30V and a 0,6 V diode voltage drop, 2% of the energy generated by the solar cells is lost in the form of heat in the blocking diodes. For a lower array voltage the loss is, of course, higher. Due to the high amount of heat generated the heat dissipation must also be taken into account.

2.5 Bypass Diodes

Another problem arises if one cell in an array breaks, resulting in a disconnection. In this case we will loose the entire string. This can be fixed by using bypass diodes. They are connected in parallel with the individual solar cells or submodules, depending on the configuration, such that the diode is reverse biased when the cells are fully illuminated, as shown in figure 10. If a cell breaks by disconnecting, the current can flow through the diode instead.



Three strings in parallel, each string has two cells in series.

Two submodules in series, each submodule has three cells in parallel.

figure 10 - The use of blocking diodes with strings and submodules

This also solves another problem, when a string is slightly shadowed. In this case the affected cells becomes reverse biased, and therefore the parallel connected bypass diode becomes forward biased and conducts. This will allow the full current to flow in the string, although the output voltage of such a string is reduced by the voltage drop that appears across the diode. In order to make full use of the bypass diodes you'll therefore have to design the array to produce a higher voltage than you need, so that a few cells are allowed to fail before the array supplies an insufficient voltage.

3. Batteries

In any spacecraft power system that uses solar radiation, the storage battery is the main source for continuous power for peak and eclipse demands of power. These factors are of course depending upon the spacecraft orbit.

The battery is a very important factor for the survival of DTUsat, and should therefore be considered very carefully.

3.1 Battery Fundamentals

Before anything is mentioned of the different battery chemistries and which to prefer, some basic battery theory will be defined.

The voltage of the battery is defined as an *open circuit voltage*, that is, the voltage when the battery is not connected to any load. This voltage is the same as the voltage the battery has obtained after a full recharge, it is also called the *battery's final voltage*. When the battery is being discharged the operating voltage, also called the terminal voltage, drops from the final voltage. Because batteries are not ideal the drop will not be a brick wall drop, but a continuos drop as shown in figure 11. The shape of the curve is chemistry dependent. In normal battery operation the operating voltage is not allowed to drop below the "end of discharge voltage". After this point the drop is very rapid. The voltage of a battery cell is given by the nominal voltage which is the average of the operating voltage over the entire discharge.

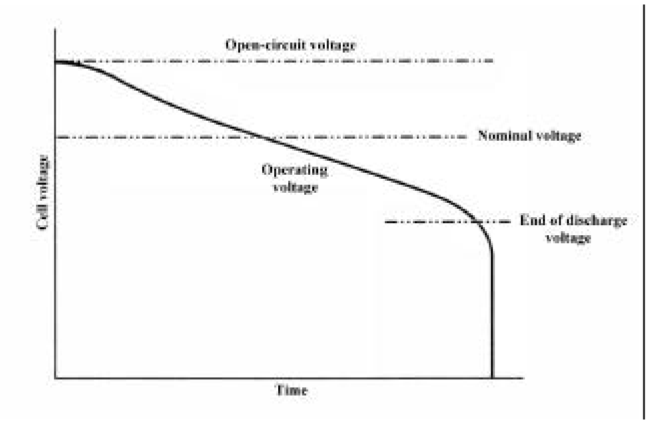


figure 11 - Voltage characteristics of a battery

Battery capacity, C, is expressed in ampere hours and gives an expression for how high a current that can be drawn form the battery for one hour. Battery charge and discharge currents are described in terms of *C-rate* and a battery with a capacity of 1000mAh has a C-rate of 1000mA. This means that the battery can deliver a current approximately of 1C for one hour, a current approximately of 2C for half on hour, and so on. All batteries do have a physical limit for how large currents that can be drawn, which is not related to C.

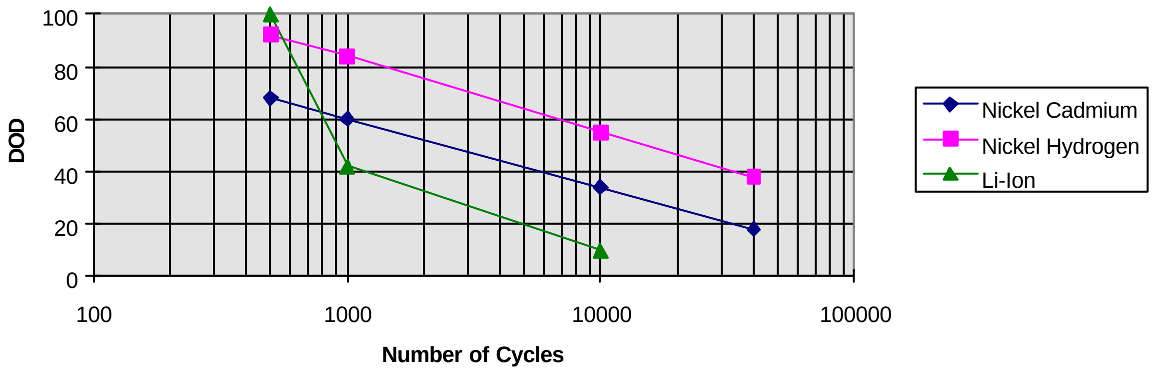
Self discharge rate indicates how much the battery will discharge while not used. The self discharge is caused by internal chemical action and is strongly temperature dependent.

The *Cycle life* of a battery is a measure for how many times the battery can be discharged and then recharged before the battery has permanently lost its ability to store energy.

Normally the cycle life is measured by performing cycles of complete discharge/recharge. The battery is then said to be worn out when the total capacity has fallen to about 80% of the initial capacity. Some manufactures quote the number of cycles for the final capacity levels as low as 50%

of the initial capacity. Therefore when comparing cycle life of batteries from different manufacturers it is important that the cycle life's are normalized to each other.

The *depth of discharge*, *DOD*, is related to the life of the battery. If the battery is fully discharged (DOD of 100%) and then recharged the battery will have the cycle life mentioned above. But if the battery is discharged to half of its capacity (DOD of 50%) and then recharged, the number of times the battery can be discharged and recharged are more than the double. Some typical data for number of cycles vs. DOD are available for NiCd cells and NiH_2 cells, some taken from [JW99] are shown in the following graph:



It has been more difficult to find information about Li-Ion and Li-Ion Polymer batteries. For Li-Ion batteries several papers, including [GE97] and [CK98] suggests that at 40% DOD about 1000 cycles can be expected, and at 10% DOD about 10.000 cycles are possible. Summed up with the typical cycle life given by the manufacturers of 500 cycles at 100% DOD, we get the line on the graph above. Unfortunately we haven't been able to find similar data for Li-Ion Polymer batteries. We have tried to contact Danionics, but they couldn't provide the information.

This clearly indicates the importance of DOD, especially for satellite operation, where the satellite will experience one cycle per orbit. The number of orbits per day can be quite high for low earth orbits (about 15 per day) - therefore DOD can be an important factor for the expected lifetime of a satellite.

The *operating temperature range* for discharge is the temperature interval in which the battery work efficiently enough to power a device. A similar temperature range is defined for charging and they may be different.

Memory effect is a phenomenon that reduce the capacity of the battery when it is repetitively discharged incompletely (DOD<100%) and then recharged. Often when a battery suffers form memory effects the capacity can be restored by one or several full discharge-charge cycles.

Energy density is the total energy that a battery can store divided by the mass or volume of the battery. This may be an important factor when physical space and/or weight is limited.

Battery impedance is measured as the internal resistance of the battery. Series connection of batteries increases the internal resistance and parallel connection decreases the internal resistance. If the internal resistance is too high the battery voltage will fall too much during discharge. High currents cannot be drawn form the battery if it has too large an internal resistance. Hence it is preferred to have as low an internal resistance as possible.

Many of the battery phenomenons mentioned above also depends on conditions to which the battery has been exposed, which are not mentioned because it is beyond the scope of this report. On the other hand the theory described gives a sufficient battery fundamental insight to understand the behavior of batteries needed for reading this report. For further reading please consult the Handbook of Batteries [DL95].

3.2 Choosing the Right Battery

When choosing the battery for DTUsat, the ideal battery would have the following characteristics, but it should be noted that a battery that satisfy all the requirements are impossible to find:

- Light weight
- Small size
- A structure that is rough and vacuum stable
- High output voltage
- Low internal resistance
- Stable operating voltage over the temperature range needed
- Safe storage over the temperature range needed
- Easy to recharge
- High cycle life
- Availability

The weight and size is important because the two parameters are limited in the satellite. It is of cause also important to have a battery that can function properly in space where the conditions are 'slightly' different from the ones at sea level. A battery that might work excellent at the earth may not work in space at all because of the different environments.

The higher the output voltage of the battery is, the fewer cells are needed to achieve the satellite operating voltage. The lower the internal resistance is, the higher current can be drawn from the battery.

The temperature plays a significant role for the battery because the batteries are chemical devices and these are affected by temperature. Chemical activity is increased at high temperatures and decreased at low temperatures, which means that the output voltage of the cell will fall as the temperature decreases and will rise as the temperature increases.

Charging the battery at too low a temperature will not destroy the battery, but a very low efficiency is achieved. Storing the battery at high temperatures reduces the life of the batteries. If the batteries are difficult to recharge too much energy is needed to control the charging process. The number of times that the battery can be charged and discharged also plays a significant role in the life of the satellite.

Properties that are not considered for this project includes cost and environmental considerations of the battery.

Before the final battery choice can be made it is necessary to know more about the properties of the different battery chemistries. There exists a lot of different battery chemistries but the most common chemistries are NiCd (nickel cadmium), NiMH (nickel metal hydride), NiH_2 (nickel hydrogen), and Li-Ion (lithium ion) and therefore only these will be considered as potential batteries[1].

3.3 NiCd and NiMH Cells

Charging NiCd and NiMH cells are very similar to each other. They both require a constant current through the entire charging period. The charging of the two types of cells differs only in figuring out when it is time to stop the charging. The cells must both be charged with a constant current. During charging the voltage of the cells rises slowly, as shown in figure 12, until the voltage reaches a peak

[1] Other rechargeable battery chemistries include: Sealed Lead Acid, Nickel Zinc, Iron Electrode, and Silver Oxide batteries etc.

($dV/dt = 0$) at time t_1. At this point the charging should be stopped for the NiMH cell, while for the NiCd the charging should be continued until the voltage has a slight decline ($dV/dt < 0$) which occurs slightly after the peak. The cells can be damaged if the charging continues past this point because the cells can obtain a fairly high temperature, which eventually might lead to an explosion.

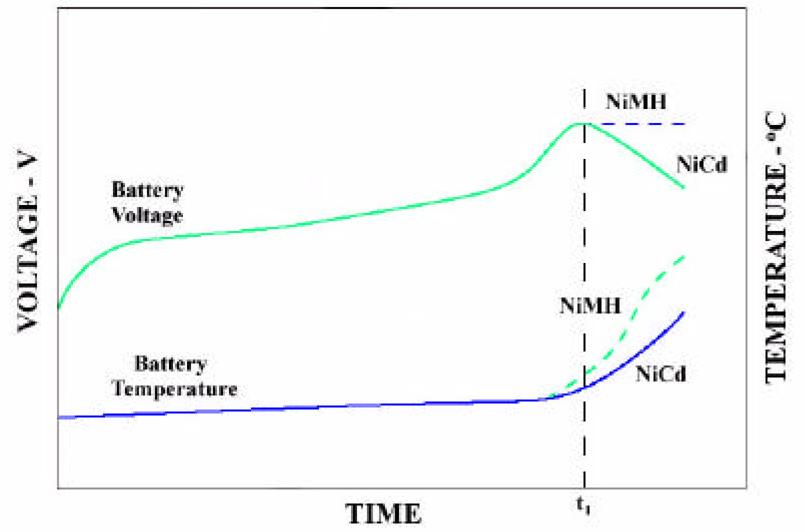


figure 12 - NiCd and NiMH charging characteristic

Especially for charging currents larger than C/2 the temperature of the cell has to be monitored because the temperature rises rapidly when the cells reaches full charge at the stop point, this is also shown in figure 12. A good battery charger for NiCd and NiMH cells relies on a combination of voltage and temperature monitoring when it decides when the cell is fully charged. It should be noted that when charging begins the cell may imitate the stop conditions and therefore the charger needs to have a delay of one to five minutes after the stop point has been detected to ensure that the cell is actually fully charged.

At currents below C/8 it can be difficult for the charger to detect the stop point, since the voltage (dV/dt) and temperature (dT/dt) slope is small compared to charge currents larger than C/2. But at currents below C/8 the temperature rise is small so the battery will not get overcharged as fast as for larger currents [MX01, page 4]. Actually by charging with currents below C/12 the cell can't be damaged by overcharging.

The discharging of NiCd and NiMH cells are also very similar to each other and the discharge characteristic is shown in figure 13. The discharge profile is very flat and the cells maintain their nominal voltage of 1.2V for almost the entire discharge period. When the operating voltage of the cells drops below 1V discharging must stop.

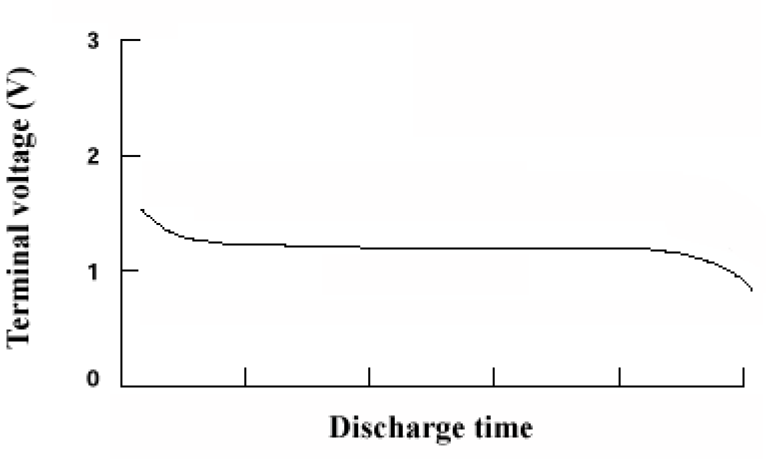


figure 13 - Discharge profile for a NiCd or NiMh cell

It should be noted that when connecting the cells in series the operating voltage drop will vary between $n \cdot V_{final}$ to $n \cdot V_{end\ of\ discharge}$, where n is the number of cells connected in series.

3.4 NiH_2 Cells

The Nickel Hydride battery has been developed for aerospace applications. The battery usually has a high capacity and is large and heavy primarily due to it's packaging [DL95]. It is consequently not suitable for DTUsat. Therefore no further will be mentioned about NiH_2 batteries in this report.

3.5 Li-Ion Cells

Lithium is the lightest metal, it has the greatest electrochemical potential of all metals and is therefore the most suited metal for battery cells. Unfortunately lithium is very reactive. If you attempt to charge a battery that contains lithium in metallic form the battery will be destroyed. On the other does lithium ions have almost as good battery properties as metallic lithium and lithium ions are not reactive as long as it stay in the ion form, and hence a battery is achieved with very good and safe properties compared to other battery chemistries.

Basically two Li-Ion types have emerged: The Coke version and the Graphite/carbon version. It is the battery negative electrode (anode) that is made of either Coke or Graphite [IB00, page 1-3]. The differences between the two types will be discussed further in section 3.9 about discharging Li-Ion based cells.

3.6 Li-Polymer Cells

The structure of Li-Polymer allows the manufactures to create a battery of almost arbitrary shape and size. This property is suited for applications where physical space for the battery is limited like in portable devices.

In a Li-Polymer battery the electrolyte is different from other types of batteries, because here the electrolyte is dry. The internal resistance of a dry electrolyte is so high at room temperature that it can not deliver sufficient current and is therefore not very useful. Currently Li-Polymer batteries reaches an acceptable internal resistance at about 60 °C. This is expected to improve in the future, therefore Li-Polymer batteries that have a sufficiently low internal resistance at room temperature is anticipated by 2005 [IB01, page 1-2]. Consequently the Li-Polymer battery technology cannot be used for the DTUsat at the present time.

Today there exist “Li-Polymer” batteries that are conductive at room temperature because there has been added some gelled electrolyte to the dry electrolyte. The correct name for these batteries is Li-Ion Polymer.

3.7 Li-Ion Polymer Cells

Most Li-Ion Polymer cells are packed in a foil package and are called “pouch cells”. This packaging method makes the Li-Ion Polymer cell simple, small, flexible and light weight. A pouch cell from the Danish manufacturer Danionics is shown in figure 14.

figure 14 - A Li-Ion Polymer pouch cell

When the pouch cell is charged and discharged, gas may be generated inside the cell and the cell may be swelling. Therefore the Li-Ion Polymer cell may not be installed in too tight a compartment [IB01, page 1-2].

The pouch cell is packed at low pressure but when the cells are brought into space where the pressure is even lower the cell may swell because of the few molecules that are inside the foil packaging. This vacuum swelling may cause the battery to malfunction. Only tests can show if a Li-Ion Polymer battery can be used in space applications.

Li-Ion Polymer based batteries are not indestructible. They require strict adherence to some rules for charging and discharging and if the rules are ignored you risk reducing the battery’s life or destroying the battery and possibly its surroundings because of explosion. Carefully designed circuits can handle the Li-Ion charging so that you avoid the above consequences.

3.8 Li-Ion and Li-Ion Polymer Charging

Unfortunately the rules for charging Li-Ion batteries tend to vary with the manufacturer. This is mainly because the technology is relatively new.

Once again, it should be emphasized that Li-Ion batteries are extremely sensitive to incorrect charging, which may result in a dangerous explosion or severely decrease in battery life and/or capacity.

When charging a typical Li-Ion battery, the charger must first provide a constant current mode until the battery voltage reaches a certain level and then a constant voltage mode. It is the design of a circuit (the charger) that can change between a constant current source and then a constant voltage source that makes it difficult. The problem is that the constant current source has a very high output impedance and the constant voltage source has a very low output impedance.

A typical Li-Ion charge cycle is shown in figure 15 where the charging process starts with a constant current mode until the battery terminal voltage reach its full charge voltage.

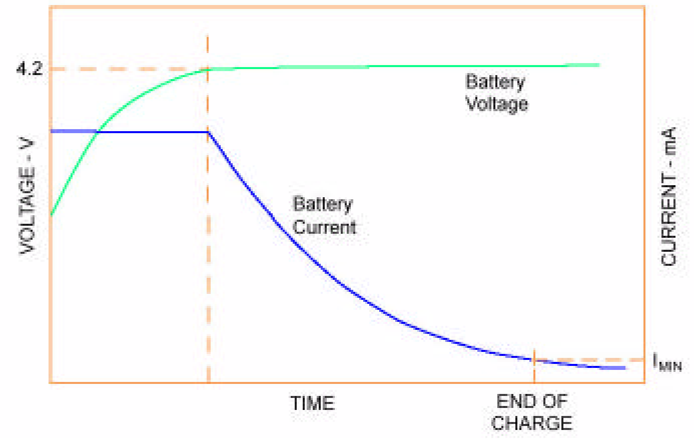


figure 15 - Li-Ion Battery charging characteristic for a battery with a final voltage of 4.2V

The final voltage is 4.2V for most Li-Ion batteries, but some manufacturer's cells have a final voltage at 4.1V. The higher voltage of 4.2V is reached because of some chemical additives.

It is when the battery reaches the final voltage that the constant current source need to shift on command to a constant voltage source. Now for the rest of the charging period, the battery is charged at a constant voltage while the charge current drops gradually. The gradual drop in charge current is due to the change of internal cell resistance. The charging stops when the charge current falls below a specified minimum value, I_{MIN} [MX02, page 4].

In the constant current mode approximately 70% of the total capacity is delivered to the battery and the final 30% during the constant voltage mode. If the terminal voltage is above the final voltage the battery is considered overcharged and when the terminal voltage is under the final voltage the battery is undercharged.

Overcharging will destroy the battery and for this reason it is important that the final charge voltage is controlled to within ±50mV of its final voltage. Undercharging will not destroy the battery, but it can greatly reduce the battery capacity as shown in figure 16.

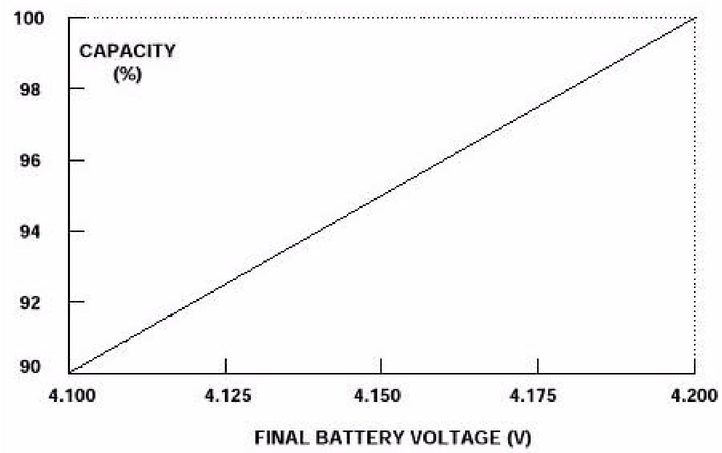


figure 16 - Effect of undercharge on Li-Ion and Li-Ion polymer battery capacity where the final voltage is 4.2V

Notice that if the battery is undercharged by only 100mV, the battery only has 90% of its full capacity [WK01, page 5.10]. Therefore it is very important that there is an accurate control of the battery voltage and current, so that the battery doesn't suffer from over- and undercharge.

3.9 Li-Ion and Li-Ion Polymer Discharging

The discharging characteristic of a Li-Ion and a Li-Ion Polymer battery is not as flat as it is for NiCd or NiMH batteries discussed earlier. The discharge profile is almost linearly decreasing from the final voltage to the end of discharge voltage as shown in figure 17. After the discharge cut off, the voltage drop is very rapid.

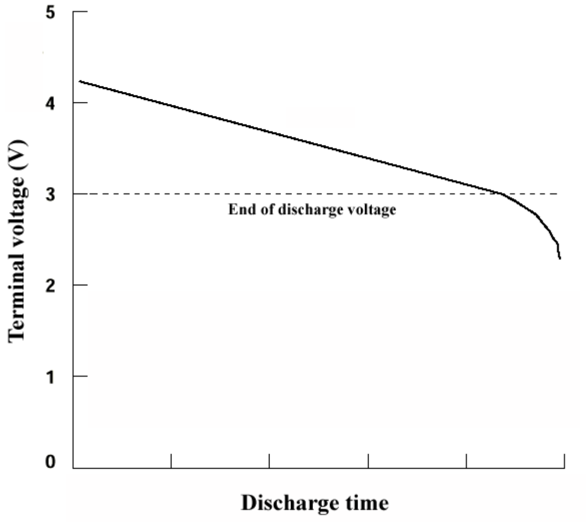


figure 17 - Discharging profile of a Li-Ion or a Li-Ion Polymer battery

The battery terminal voltage will vary from 4.2V to about 3.0V depending of how deep the battery is discharged. Normally the batteries is never discharged below 3.0V under normal operation. It is extremely urgent that the battery is not discharged below the end of discharge voltage, because this so called over discharge can destroy the battery cell [WK01, page 5.4].

The discharging differences between the two types of Li-Ion cells, the coke and the graphite version are not shown in figure 17. The graphite version has a much flatter discharge profile than the coke and all the useful energy stored in the battery can be retrieved by discharging the graphite cell to 3V, whereas the coke version has to be discharged to 2,5V to retrieve the same amount of energy [IB00].

3.10 Li-Ion Chemistries Compared to NiCd and NiMH

Which rechargeable battery to use is a choice between NiCd, NiMH, Li-Ion, and Li-Ion Polymer. In order to make the right decision it is necessary to look at the advantages and disadvantages for the four kinds of batteries. The following table shows a comparison of typical values for the battery technologies discussed in this document. Li-Ion and Li-Ion Polymer based batteries are new technologies that are constantly developing so the values for these batteries are also constantly changing.

	Li-Ion	Li-Ion Polymer	NiMH	NiCd
Energy density (Wh/kg)	90-120	110-150	50-60	30-40
Energy density (Wh/L)	260-300	280-320	180-220	120-150
Operating voltage per. cell (V)	3.6	3.6	1.2	1.2
Cycle-life (80% of initial capacity)	500	500	500	500
Self discharge (% / month)	6	6	20	15
Memory effect	No	No	Some	Yes
Overcharge tolerance	Very Low	Low	Low	Moderate
Easy to recharge	Moderate	Moderate	Yes	Yes
Well known for space applications	No	No	No	Yes
Max long term load current (mA)	<2C	<1C	<2C	<3C
Internal Resistance at 25°C (mΩ)	150-250	300-400	150-250	100-200
Charge operating Temperature (°C)	0 to 45	0 to 50	0 to 45	0 to 45
Discharge operating Temperature (°C)	-20 to 60	0 to 60	-20 to 60	-20 to 60

Notice that Li-Ion and Li-Ion Polymer batteries have higher energy densities per weight and volume. This means that the battery of the same capacity is physical smaller and lighter. Another important factor for Li based batteries is the higher operating voltage per cell, this means that fewer cells are needed to obtain the total operating voltage.

Lithium based batteries also have a low self-discharge, which means that the battery maintains its charge while not used. NiMH and NiCd have a self-discharge of at least 2.5 times as high. The self discharge rate is not very important for the DTUsat while it is in orbit because the battery is used most of the time. By including a test plug it is possible to charge the battery in the satellite while it is in the P-POD. We do not, however, know how short before launch this may happen therefore the self discharge rate may have some relevance.

The memory effect of the NiCd cells will cause problems if not properly handled. This can be done by completely discharging and recharging the battery a couple of times, for instance every 150 cycles. If the remaining systems of the satellite must function properly during the entire reconditioning phase we need two sets of batteries that complement each other. While the first set is being reconditioned the other one can be used for normal operation and vice versa. This makes the system rather complex and it should be avoided for a small satellite like DTUsat.

Ease of recharging the battery, and overcharge tolerance are two important factors, but for either chemistry a charge control system is needed if we want to charge at a moderate to high rate [ES95, page 11-34], which is necessary because of the short duration of one orbit. Therefore this parameter is not so critical after all.

If the chemistry is well known for space application more material exists on the subject and possibly some tests are not needed. Especially Li-Ion and Li-Ion Polymer technology features a lack of field history, but if the battery is sufficiently tested by us this should not matter.

In applications where the battery has to deliver a large amount of current, several amps, Li-Ion Polymer batteries cannot be used. This is because Li-Ion Polymer batteries have a high internal impedance which means that high currents cannot be delivered efficiently. There is no need for currents above 1.0A in the DTUsat. Since the highest expected current is about 0,5 A this is not going to be a problem.

The operating temperature ranges are some very critical factors but the different chemistries does not differ that much.

As can be seen from the table no battery chemistry is perfect. But this discussion shows that a Li-Ion battery is the best choice for DTUsat. Of course other factors like availability must be considered before we can make the final choice. We will return to this subject in section 9.

4. Space Environment

The environment for electronics in a satellite orbiting the earth differs quite a bit from electronics being used on the earth. Apart from the lack of pressure, the satellite will experience temperatures from -40°C to +80°C, and it will be exposed to radiation. This includes the background radiation and high energy particles that can cause severe situations (for instance latch up) if they are ignored. In order to minimize these problems special versions of standard electronic components have been developed for space applications. These components are very expensive compared to commercial off the shelf (COTS) components, typically they are about 100 to 1000 times more expensive. Therefore the DTUsat project, like most other student satellite projects, are trying to use COTS components whenever possible.

4.1 Radiation

The space radiation environment near the Earth consists mostly of radiation from two different sources, namely: The solar wind and two radiation belts.

The solar wind consists of electrons, protons and a small percentage of heavier ions. The energy and density of these particles depends heavily of the solar cycle which has an 11 year period. The last peak in solar activity occurred in 2001. In the lower equatorial regions of the Earth, the magnetic field deflects the solar wind, but in the polar regions, even relatively low energy particles can penetrate close to the surface - this can be seen visually in the form of northern lights.

Another dominant contributor is the 2 major radiation belts called the Van Allen belts. These belts consist of electrons and protons. The inner belt is relatively small, and has peak intensity at 2000 to 3000 km altitude. This is fortunately much further out than our satellite's orbit, but the belts are closer to the earth at the two poles, which is the reason that polar orbits are subject to a higher radiation dose. The outer belt has peak intensity at about 10000 to 20000 km altitude, and mainly contains electrons. In LEO (< 1000 km) orbits the typical average radiation level is about 1 to 2 krad/year.

In order to minimize the impact of radiation shielding is used, but due to the low weight constraint of 1 kg we can only allow a very limited amount of shielding.

4.2 Single Event Effects

A single event effect results from a single, energetic particle. If such a particle hits a component, you might encounter two different errors:

- Single Event Upset (SEU), changes the state of the device, this includes bit flips. This effect is not electrically destructive, although a bit flip might destroy program code or data. This can be handled by an Error Detection and Correction (EDAC) circuit.
- Single Event Latch Up (SEL), causes an effective short circuit of the source or drain of a MOS transistor to ground. This is due to the parasitic transistors automatically introduced in such a circuit. If a high energy particle hits the 'gates' of these transistors they will begin to conduct. This will effectively short circuit the source or drain to the outer P-layer which is most often connected to ground.

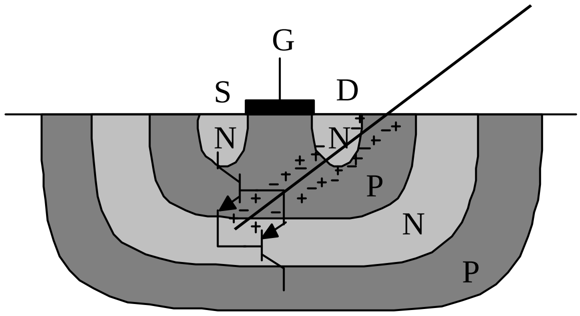


figure 18 - High energy particle hitting an N-MOS transistor (rough outline)

By turning off the power to the transistor the short circuit will be removed, and the parasitic transistors will no longer conduct. It is evident that it is necessary to turn off the power very fast before any harm has been made to the device.

Silicon-on-Insulator (SOI) and Silicon-on-Sapphire (SOS) technologies removes the fourth layer and are consequently not prone to SEL.

Because only high energy particles causes these single event conditions shielding is of no use since the particles will pass straight through.

4.3 Radiation Hardness

As mentioned earlier the average radiation level a satellite in LEO orbit encounters is about 1 to 2 krad/year, but solar flares can induce additional radiation.

Components can be divided into three different radiation tolerance groups: Commercial (Rad Soft), Rad Tolerant, and Rad Hard. They have the following properties:

	Total Dose	SEU Threshold	SEU Error rate
Rad Soft	2 to 10 krad (typ)	5 Mev/mg/cm^2	10^{-5} errors/bit-day (typ)
Rad Tolerant	20 to 50 krad (typ)	20 Mev/mg/cm^2	10^{-7} to 10^{-8} errors/bit-day
Rad Hard	>200 krad to >1 Mrad	80-150 Mev/mg/cm^2	10^{-10} to 10^{-12} errors/bit-day

Because our satellite is designed for only 1 year of operation it doesn't seem impossible to use commercial components with regard to the total dose.

5. Orbit

Our satellite will be launched as a secondary payload together with probably 17 other Cubesats and we do therefore not have any influence on the choice of orbit. Furthermore since the launch provider hasn't been chosen, yet, we don't know into what orbit out satellite will be put. Therefore we can't optimize the solar cells and/or batteries for the final orbit. We can, however, design for a likely worst-case scenario.

The Cubesats that will be launched in May 2002 will be put into a sun-synchronized orbit at 650 km. Since the local time of the orbit is not yet determined the satellites will be subject to a sunshine duration of 60% to 100% per orbital period [JP01].

We will therefore design the power supply for a polar orbit at an altitude of 650 km. The following calculations are meant for getting an overview of the orbit only. For exact and final calculations the Spenvis program will be used. This is a web-based program for solving several space related problems. It has been made available on the internet by ESA [SP00].

In order to find out how long a duration of shadow we can expect, we need to derive an expression for θ as a function of time. We can use Newton's law of gravity [GC97, chapter 10] to find the velocity of the satellite $v = \sqrt{\frac{G \cdot M}{r}}$,

where G is the universal gravitational constant = $6{,}670 \cdot 10^{-11}$ Nm^2kg^2,
M is the mass of the earth = $5{,}97 \cdot 10^{24}$ kg, and
r is the distance from the center of the earth to the satellite = 6370 km + 650 km = 7020 km

That is: $v = \sqrt{\frac{6{,}670 \cdot 10^{-11}\,\mathrm{Nm^2kg^2} \cdot 5{,}97 \cdot 10^{24}\,\mathrm{kg}}{7{,}02 \cdot 10^{6}\,\mathrm{m}}} = 7530\ \mathrm{m/s} = 7{,}5\ \mathrm{km/s}$.

The angular distance traveled is $\theta = \frac{v \cdot t}{r}$, where t is the time in seconds.

Therefore the angular velocity, given by: $\omega = \frac{d\theta}{dt} = \frac{v}{r} = \frac{7530\ \mathrm{m/s}}{7{,}02 \cdot 10^{6}\,\mathrm{m}} = 0{,}00107\ \mathrm{rad/s}$, and the duration of one orbit is $t_{orbit} = \frac{2 \cdot \pi}{\omega} = \frac{2 \cdot \pi}{0{,}00107\ \mathrm{rad/s}} = 5860\mathrm{s} \approx 98\,\mathrm{min}$. That is, the satellite will perform $\frac{24 \cdot 60\ \mathrm{min/day}}{98\ \mathrm{min/orbit}} = 14{,}7\ \mathrm{orbits/day}$, or $14{,}7 \cdot 365 = 5360$ orbits / year.

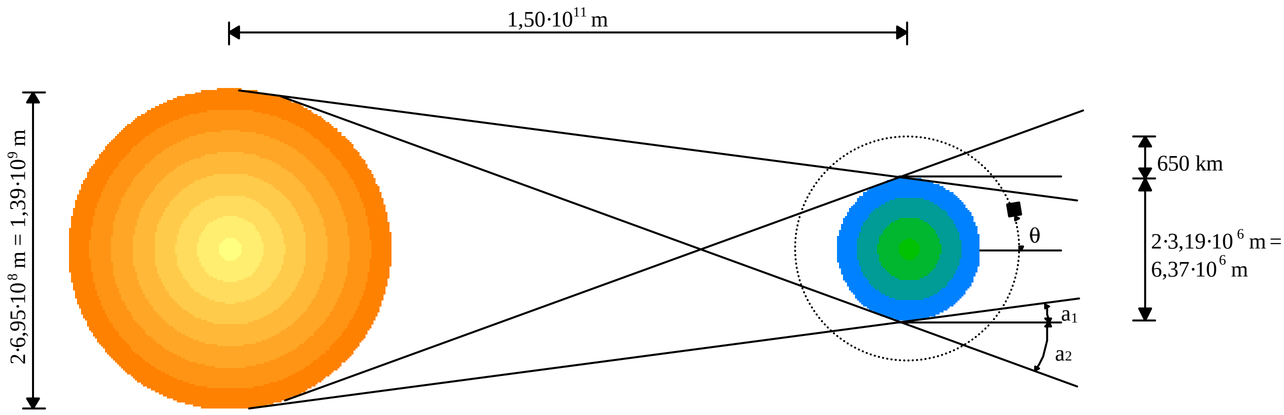


figure 19 - Sun - Earth - DTUsat geometrics

We will now look at the maximum duration of one pass through the shadow. We first notice that the satellite will not pass momentarily from illuminated to complete shadow, but due to the large distance between the sun and the earth as opposed to the radius of the earth the angles a_1 and a_2, as shown in figure 19 are very small. We can therefore ignore the partial shadow phase by using the earth's radius as a mean to determine when the satellite is illuminated: If the satellite is in shadow $\left|r_{sat} \cdot \sin(\omega \cdot t)\right| < r_{earth}$ and $\cos(\omega \cdot t) > 0$. These equations solves into: -1036 s < t < 1036 s => t_{shadow} = 2 · 1036 s = 35 min. That is: 35min/98min = 36% of one orbit is taking place in the shadow of the earth.

We must therefore design the battery so that it can power the satellite for 35 minutes at a reasonably low DOD. Likewise the solar cells must be able to charge the battery while running the satellite when the satellite is traveling through the illuminated phase.

6. Power Budget

After long discussions with the other groups involved in the project we have reached the tentative power budgets seen in appendix F. These numbers will be used to calculate the average power usage, and the power needed when everything is operating at the same time.

A few comments about the duty cycles are appropriate. When the attitude control system is measuring the orientation the coils are turned off, otherwise the magnetic field induced by the coils would destroy the measured data. Therefore the duty cycle of the magnetorquers are 990 ms/s. When detumbling the satellite they will require somewhere between 50 and 150 mW, but when the satellite is stabilized they are expected to lower the power consumption to less than 50 mW. This is a major difference and we will therefore create a power budget for both detumbling and stabilized operation.

The onboard computer is expected to run at all times. A boot up after a reset is expected to last for less than 1 second, and because it has to read some data from a read only memory it will require a current of 110 mA. For worst case calculations we expect no more than one boot per 30 minutes, or about 3 per orbit. Uploading of data to the computer requires writing to the flash memory, also consuming 110 mA. In our average calculations we expect one upload per day for a duration of 10 minutes.

The radio contains a receiver and a beacon transmitter both of which will be operating at all times. The transmitter and PA stage will only operate when the satellite can be seen from our ground station, this time interval is called a window. The Attitude Group has estimated these occurrences as no longer than 4 x 15 minutes (probably shorter) per 12 hours, with 4 orbits containing windows of various length up to 15 minutes, and the next 8 containing no windows. If everything works out well the satellite will need to spend most of these windows to transfer pictures and housekeeping data to the ground. We therefore expect the transmitter to operate for the entire window, or 2 hours per day. It is interesting to note that programming the flash and transmitting data does not occur at the same time. Because the power consumption of the transmitter is a factor 10 higher than that of programming the flash, and because we assume that data is being transferred from the satellite for the entire window we don't need to consider the power consumption of uploading data.

The tether is expected to consume 5 mA at all times when deployed. Since ejection of the tether will effectively stop the attitude control system from working (except for measuring the position) we can actually disregard the tether because it consumes less power than the magnetorquers - this has, however, not been done.

Finally we have estimated the camera to be taking pictures for 5 minutes per orbit, which is most likely a lot more than we will see in practice. But this high time frame makes the power usage of the camera less important, and currently the camera group doesn't know the exact amount of power needed.

The numbers mentioned in the power budgets are for beginning of life operation. Due to radiation these values will most likely increase during the life of the satellite. One radiation test made by the Stensat Group showed that the power consumption of a PIC16C77 micro controller increased by a factor 4,5 just before it stopped working due to radiation. At this time it had been exposed to 35 krad [HH00]. Because of the high dose rate (many rad/s) it is impossible to say exactly how long the chip will actually operate in orbit. It may work fine for just one year, or up until 5-10 years has passed.

Our own radiation test showed, that the power consumption after a dose of 5 krad didn't change the power consumption of a Max890 circuit at all (the expected dose of radiation in orbit is 1 - 2 krad/year). We're still awaiting the results of similar tests from the other hardware groups in the

DTUsat project. When we receive these results we will be able to calculate the overall power consumption after radiation.

6.1 Detumbling

The above mentioned values results in the following results when the satellite is detumbling:

	U (V)	I (mA)	Duty cycle	Average Power (mW)	P when not transmitting (mW)	P when transmitting (mW)
Magnetorquers	3,3	46	0,99	150	150	150
Magnetometer 1	3,3	20	0,01	0,66	0,66	0,66
Magnetometer 2	3,3	500	0,00003	0,0495	0,0495	0,0495
Sun sensor	3,3	4	0,02	0,264	0,264	0,264
OBC	3,3	50	1	165	165	165
Boot	3,3	110	0,0006	0,2017	0,2017	0
Upload	3,3	110	0,0069	2,50	0	0
Beacon	3,3	2	1	6,6	6,6	6,6
Receiver	3,3	20	1	66	66	66
Transmitter	3,3	20	0,0833	5,5	0	66
PA	3,7	270	0,0833	83,25	0	1000
Camera	3,3	25	0,0556	4,58	4,58	4,58
Tether	3,3	5	1	16,5	16,5	16,5
Total:				**501,1**	**410,0**	**1476**

We notice that the most demanding loads are the magnetorquers, the onboard computer, and the radio, especially the PA-stage.

The total power usage numbers are interesting. First the average power consumption can give a rough first estimate of how feasible the budget is. Since 501 mW is about 1/3 of the expected input power provided by the solar cells (see section 8.4) this doesn't seem unrealizable. Because the transmitter uses a lot of power it is interesting to examine the power usage when transmitting and not transmitting. These numbers are the basis for our per orbit calculations in section 6.3.

6.2 Stabilized Operation

When the satellite after some time (probably weeks) is stabilized the magnetorquers will require less power. The only difference from the detumbling mode is that the magnetorquers use 1/3 of the power, which results in the following numbers:

	U (V)	I (mA)	Duty cycle	Average Power (mW)	P when not transmitting (mW)	P when transmitting (mW)
Magnetorquers	3,3	15,3	0,99	50	50	50
Magnetometer 1	3,3	20	0,01	0,66	0,66	0,66
Magnetometer 2	3,3	500	0,00003	0,0495	0,0495	0,0495
Sun sensor	3,3	4	0,02	0,264	0,264	0,264
OBC	3,3	50	1	165	165	165
Boot	3,3	110	0,0006	0,2017	0,2017	0
Upload	3,3	110	0,0069	2,50	0	0
Beacon	3,3	2	1	6,6	6,6	6,6
Receiver	3,3	20	1	66	66	66
Transmitter	3,3	20	0,0833	5,5	0	66
PA	3,7	270	0,0833	83,25	0	1000
Camera	3,3	25	0,0556	4,58	4,58	4,58
Tether	3,3	5	1	16,5	16,5	16,5
Total:				**401,1**	**310,0**	**1376**

It is interesting to note that the expected average power consumption will be lowered by about 19%. This will by far oppose the degradation of the solar cells due to radiation, and it will help neutralize some of the increased current drawn from the remaining circuits, also due to radiation.

6.3 Energy Calculations

We will now use the above results in order to determine the energy demands of the battery and solar cells for the orbit calculated in section 5, that is: 98 min/orbit, with 35 min in the shadow. Three different scenarios are interesting:

1. The satellite transmits data to the earth while it is in the shadow (worst case)
2. The satellite transmits data to the earth while it is illuminated
3. The satellite doesn't transmit data (best case)

There are two numbers we're particular interested in. These are the depth of discharge (DOD) of the battery, and whether it is possible to recharge the battery in one orbit. In general the lower the DOD the more cycles the battery can pass before it is worn out, as shown in section 3.1. As we can expect about 5400 orbits per year, and a DOD of 10% would allow for about 10.000 cycles we can expect the battery to be operational for almost 2 years. Since these numbers are only a guidance, and are valid for Li-Ion batteries and not Li-Ion Polymer, we think that it is important to keep the DOD below 10%, and preferably even lower.

It is obvious that if it is impossible to charge the battery completely in one orbit it will be completely drained after a couple of orbits. It is also worth to notice that the battery will experience the highest DOD after a transmission has been performed while the satellite is in shadow. The result of these calculations can be seen in appendix F. We have made the calculations for two batteries with a capacity of 700 mAh, and 1500 mAh. The input power from the solar cells has been set to only 1000 mW/s. This gives us some headroom for efficiency losses in the DC/DC converters, diode losses, and radiation degradation of the solar cells - the initial value of the solar cells is expected to be about 1600 mW/s, as can be seen in section 8.4.

From these calculations we note that even when the satellite is transmitting data when in shadow the battery can be completely charged in the following illuminated phase. Also we note that for the 1500 mAh battery the DOD in this case is a little less than 10%. Finally we note that the DOD for the 1500 mAh battery for an average orbit is about 5%. If we're using Li-Ion batteries we can therefore expect a minimum of 10.000 cycles, which allows about 2 years of operation.

7. Electrical Power System Architecture

The satellite power system can be divided into three main categories: Controlling the solar array, charging the battery and regulating the bus voltage.

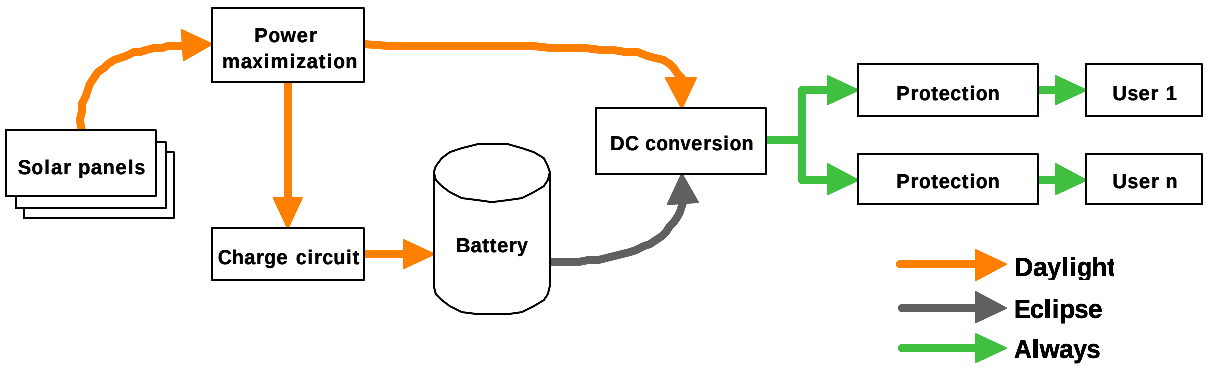


figure 20 - Architecture of the power system

The electrical power generated by the solar array must be controlled so overcharging the batteries is avoided, this is especially important if no battery charger is used. If the solar panels produce more energy than required, this extra energy must be reduced so undesired internal satellite overheating is avoided.

If a battery charger is used, this circuit prevents the battery from overcharging. Some of the subsystems may need a stable power source requiring the bus voltage to be regulated.

Before the final choice of electrical power system architecture is made, some considerations about the different power control techniques and electrical topologies must be made.

7.1 Power Point Tracking System

A power point tracking (PPT) system is a series coupled device that extracts exactly the amount of power from the solar panels that is needed.

The PPT system is a high frequency switching DC/DC converter that by changing the duty cycle can adjust the output voltage. The PPT system measures the output power delivered from the solar panels. It then shifts the voltage one step up or down and measures the power again. The two results are compared and the voltage will be shifted either up or down depending on the demands of the satellite.

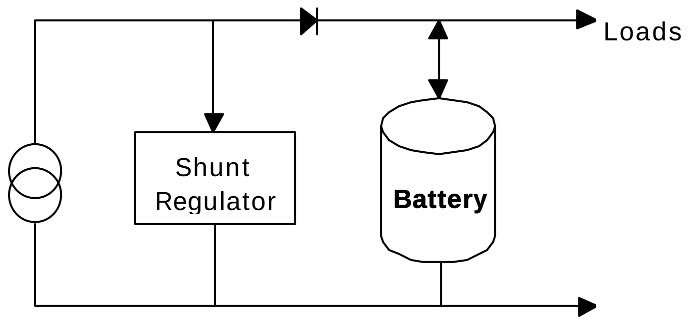
Even though the theory sounds straightforward, it is a fairly complicated system to design, especially because the total output power from the solar cells is less than 2W. Therefore the PPT system itself may only consume a very limited amount of power, in order to achieve a higher power output when using the PPT system than when not. Because of these issues we don't expect to design such a system for DTUsat.

7.2 Direct Energy Transfer (DET) Systems

As the name refers to, the power from the solar panels is directly coupled to the battery and the loads. This can result in some problems: The extra power generated by the solar panels must be limited, in order to avoid internal satellite overheating. This can be done by adding a shunt regulator (SR). This device is connected in parallel with the solar cells and shunts the solar array terminals when the voltage level exceeds some threshold. This overheating protection is necessary for large satellites whose solar arrays produce excessive amounts of power. For a picosatellites like the DTUsat this may not be critical, but we need further thermal calculations before this can be determined. If the power system does not contain a battery charger, the SR circuit will control the battery voltage by shunting the solar array when the output voltage from the solar panels becomes higher than the threshold.

7.2.1 Unregulated DC Bus

The voltage from the solar cells minus the voltage drop from the blocking diode is the voltage on the DC-Bus when the cells are illuminated, and when not the voltage equals the voltage at the battery terminals, as shown in the figure below.



The battery will also deliver power while the solar cells are illuminated if the load current is so high that it makes the solar cell voltage drop to the same level as the battery.

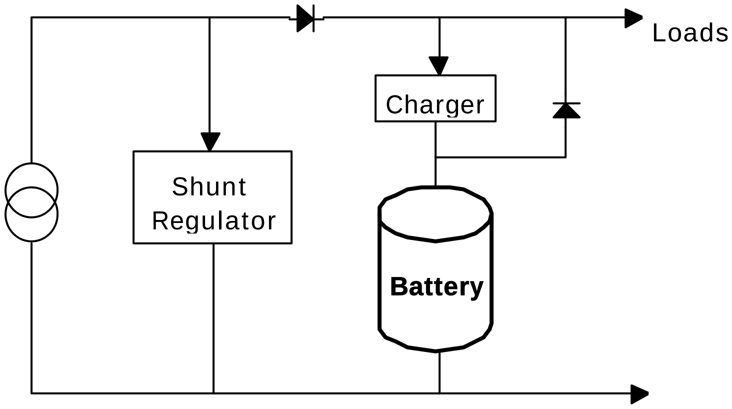
The advantages of this system are that no energy is spend on controlling circuits so more energy may available for the loads. On the other hand, the above configuration requires the shunt regulator to set the maximum voltage for the battery. Therefore the solar cells and batteries must be fairly accurately matched if the system has to offer a reasonable efficiency.

If the load is not using too high a current so that the solar panels can obtain a stable output voltage, the voltage at the DC bus will not vary too much while the solar cells are illuminated, but when the solar cells are not illuminated the load voltage equals the battery voltage which varies as the battery is being discharged.

If the current from the solar panels is sufficiently small, and the battery chemistry used is NiCd or NiMH it is possible to use this configuration that don't feature a charge circuit. These two types of batteries can survive overcharging for quite some time, provided that the charge current is sufficiently small. To see if it will work or not further investigation is needed, but NASA advises against charging batteries without a charge control circuit [ES95, page 11-34], and we thus think that this is a poor solution that should be avoided.

7.2.2 Unregulated DC Bus With Battery Charge Control

This topology works similar to the above, but now the charging of the battery is controlled by a dedicated battery charger, as shown in the figure below.



A battery charger must have a higher input voltage than the charging voltage so the voltage from the solar panels must be at least about 0,5V higher than the final battery voltage.

The battery is protected against overcharging by the charging circuit, and when the solar panels are illuminated the battery diode is reversed biased. This diode will prevent the battery from not being charged through the charging circuit.

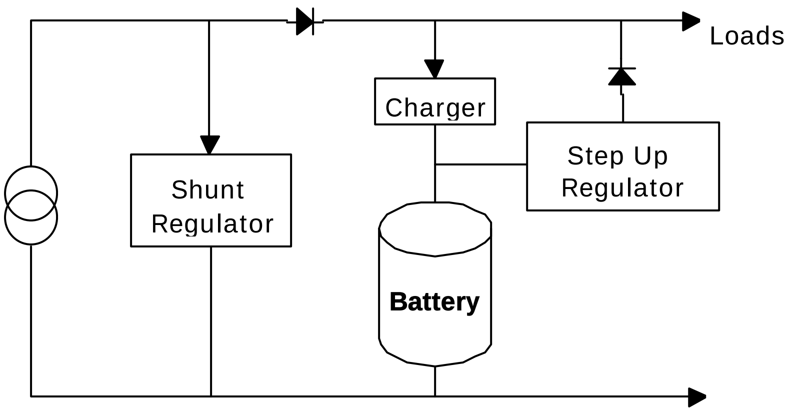
During eclipse the voltage from the solar array is 0 V and the battery diode will be forward biased, thus allowing the battery to discharge directly to the load through the diode.

The load voltage is provided by the battery and the load voltage varies as the battery is being discharged. Especially if many batteries are connected in series this voltage variation can have a large variation interval.

If the loads are critically about the quality of the load voltage this topology can be supplemented by a DC/DC converter.

7.2.3 Partly Regulated DC Bus

The advantage of this topology, shown in the figure below, is a more stable load voltage.



The step up converter will convert the battery voltage to a predetermined voltage independent of the battery voltage. This predetermined voltage must have a value so that the battery diode will be reversed biased while the solar panels are illuminated. Otherwise the battery will be discharged even when the solar arrays are illuminated.

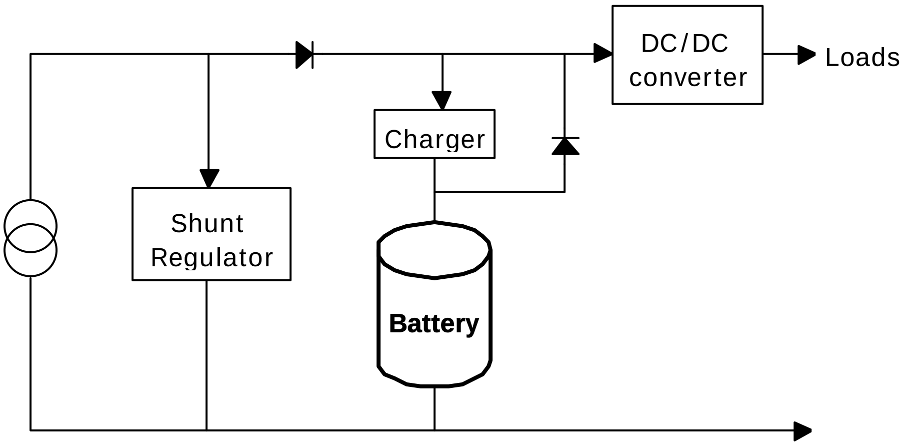
The disadvantage of this system is that it is very inefficient because of losses in the step up converter combined with the voltage drop from the battery diode.

The load voltage is determined to be the voltage from the solar panels *or* the terminal voltage of the battery. If the loads require a lower voltage an additional DC/DC converter must be added.

One problem is, that while the battery is charging the converter will consume power which makes the system even more inefficient. This may also course that the charger cannot charge the battery properly. While the battery is being charged, the output of the converter will not be loaded and this may also rise additional problems.

7.2.4 Fully Regulated DC Bus

The fully regulated DC Bus works similar to the partly regulated DC Bus, but it can provide a more stable load voltage. Also the load voltage can have an almost arbitrary value, preferably close to the voltage of the solar cells, the battery, or both.



It is the DC/DC converter that provides the stable load voltage and this converter must be able to deliver the same output voltage whether it is supplied by the solar panels or the battery.

If the load voltage is defined to be lower than the battery voltage, which is also lower than the voltage provided by the solar cells, a step down regulator is required. If, on the other hand the load voltage is about the same as the battery voltage a different solution must be used. Depending on the DOD and the temperature of the battery the battery voltage can be both higher or lower than the load voltage. A converter that can provide both a step up and a step down function, depending on the input voltage, is required.

This topology still suffers from a diode voltage loss from the battery diode and the losses in the DC/DC converter.

8. Choice of Solar Cells

8.1 Blocking and Bypass Diodes

Because the solar arrays on DTUsat are body mounted all the cells will never be illuminated at the same time. Therefore we *must* use blocking diodes. Unfortunately this results in a voltage drop of about 0,6 V, and therefore we get a fairly large loss: $\frac{0{,}6\ \text{V}}{6{,}0\ \text{V}} = 10\%$.

We've also considered the use of bypass diodes. Due to the small area that can be assigned to solar cells on DTUsat we can't afford to put extra cells in series. We would therefore not get any improvements by using bypass diodes. For instance if a cell breaks we will not only loose the cell itself, but also get a voltage drop across the bypass diode. For 3 cells in series, where one is broken, each with a nominal output voltage of e.g. 2,1 V we would get: $2{,}1\ \text{V} \cdot 2 - 0{,}6\text{V} = 3{,}6\text{V}$, and the blocking diode will add another diode voltage drop.

8.2 Cover Glass

Most vendors offer their cells without cover glass. This allows the consumer to decide what kind of cover glass they want to use. Quite often the options are, however, very limited due to requirements like temperature gradients, requirements for reflection etc.

One options is, of course not to use cover glasses at all. One reason for doing this is to reduce the weight. One reason for using cover glass is to protect the cells from the space environment, especially energetic protons that causes the efficiency to drop, and micro meteorite/debris impacts.

8.3 Configuration

It was decided to use body mounted solar arrays early in the project, and after the payloads were found the SEG group realized that it would be impossible to mount solar cells on all 6 sides of the satellite. Therefore one side of the satellite is reserved for the camera, tether, and antennas.

The DC-bus voltage has been set to 3,3 V. This was done fairly early in the project since this is an important parameter for the choice of other components for the subsystems. 3,3V requires a battery of about 3,6 V (for instance 3 NiCd cells in series or a single Li-Ion battery). The battery chargers we've considered for the project all requires at the least 4,5 V in order to be able to charge such a battery configuration. We'll therefore need 4,5V + 0,6V = 5,2V. Most Si-cells deliver about 0,5V. We'll therefore need: $\frac{5{,}2\text{V}}{0{,}5\text{V}} = 11$ cells in each string.

On average, dual and triple junction GaAs cells deliver a voltage of about 2,1V, and we'll therefore need $\frac{5{,}2\text{V}}{2{,}1\text{V}} = 2{,}48 \Rightarrow 3$ cells in series.

Due to the high number of Si cells needed, and the low efficiency of Si cells we've decided not to use Si-cells. Instead we'll focus on dual and triple junction GaAs cells, in which case we'll need 3 cells in series. Depending on the size of the available cells we can use 1 string per side or we can connect 2 or even 3 strings in parallel on each side of the satellite.

8.4 Choice of Vendor

Our search for solar cells of high efficiency (>20%) resulted in 3 companies: CESI (Italy), Emcore (US), and Spectrolabs (US). It is important to note that exporting high efficiency solar cells from America is not a trivial task, since space-rated solar cells are treated as military products. One of the

Japanese Cubesat projects didn't succeed in purchasing cells from Spectrolabs. They had to use some cells made by Sharp in Japan with a lower efficiency. It is therefore preferable if our supplier is European, or at least has an European office (which Emcore does) that supposedly knows how to twist the rules.

CESI provided the cells for the Danish Ørsted satellite, and Flemming Hansen, DSRI, tried to contact them in order to get a quote for a price for our project. It turned out that CESI is about to finish designing some triple junction cells, which Flemming Hansen suggested could get a 'free' flight test with our satellite. In this manner the price for the cells should be minimal. Unfortunately we haven't got any feedback from CESI.

Another possible vendor is Emcore. They produce triple junction cells with an efficiency of up to 26,7%. We've got some quotes for 4x2 cm^2 cells and their standard size 3,716 x 7,61 cm^2 cells. Unfortunately these space rated cells are rather expensive. Especially the 4x2 cm^2 ones compared to the size of the cells.

Our third option is Spectrolabs, as mentioned before it might become a problem to purchase cells from them due to export restrictions. They operate an e-store that offers 2nd class cells that aren't of high enough quality for true space missions, but they are fine for our mission. We have quotes for cells with a guaranteed minimum efficiency of 19%. Since the area of the cells is larger the overall output from the cells equals a configuration with the 4x2 cm^2 Emcore cells.

Size, efficiency	CESI	Emcore	Spectrolabs
4 x 2, 26%	possibly low	$195	
4 x 3, 26%		unknown	
3,7 x 7,6, 26%		$295	
3,2 x 6,9, >19%			$30 (box of 50 cells)

Note 1: The cells from Spectrolabs includes cover glass, the ones from Emcore does not.
Note 2: The cells from Spectrolabs are available in boxes of 50 pieces, total $1350, including cover glass.
Note 3: The cells from Spectrolabs are also available in a >16% variant for $585 for 50 pieces, incl. cover glass.

Spectrolab also supplies some cells in the same size with a lower efficiency (apx 16 %) that are sold for $270 for 50 pieces without cover glass. Mogens Blanke recommends that we purchase cells with cover glass because it is a tedious, though not impossible, job to mount them ourselves. Mogens Blanke's experience from the Danish Ørsted satellite also says that about 50% of the cells will break during mounting.

The cell sizes mentioned in the above table suggests a number of different configurations - all of which includes cells on 5 of the 6 sides of the satellite. Since no data is available from CESI their cells are not included in the following table:

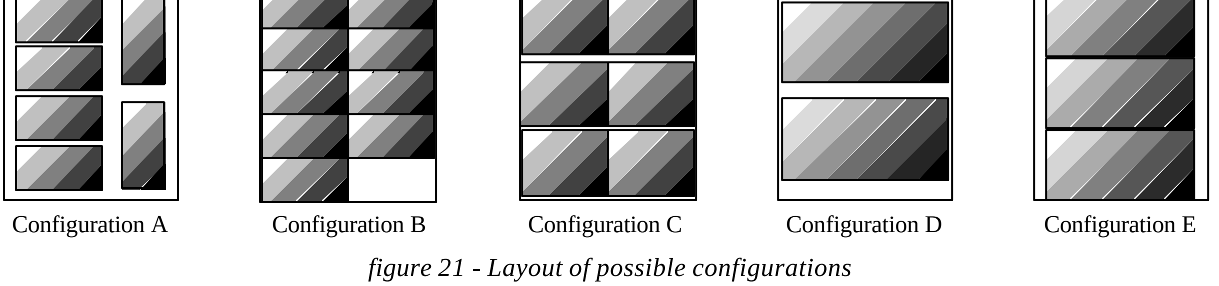


figure 21 - Layout of possible configurations

			Per side		Per satellite		
Cell size	Vendor	Efficiency	#cells	Area [cm^2]	Output [W]	Price [USD]	Cfg
4 x 2	Emcore	26 %	6	48	1,68	5900	A
4 x 2	Emcore	26 %	9	72	2,52	8800	B
4 x 3	Emcore	26 %	6	72	2,52	unknown	C
3,7 x 7,6	Emcore	26 %	2	55	1,93	3000	D
3,2 x 6,9	Spectrolab	> 19%	3	65	1,66	450	E

Note 1: The price is for the exact number of cells needed for one satellite.
Note 2: The output has been calculated with the sun normal to the surface of the cells: $P=x \times Area \times Efficiency$, where x = 1350 W/m^2.

By discussing the available size on the sides of the satellite with the MEK group, configuration B and C seems impossible, and since they are rather expensive we prefer not to use these configurations anyway. These configurations do, however, provide a good redundancy, since two, respectively three strings are put in parallel.

Configuration D is either not very useful. Due to the large size of the cells only two cells can fit any side of the satellite. These arrays will therefore only deliver 4,5 V. This has to be passed through a blocking diode with a voltage drop of 0,3 - 0,6 V leaving only about 4,0 V for the internal bus that is supposed to charge the battery. The battery chargers we’ve considered requires at the very least 4,3V in order to charge the battery, consequently this configuration requires a step-up converter. Most of these suffers from low efficiency. We therefore don’t want to use this configuration if we don’t have to.

Configuration A will definitely be able to fit on the satellite, and it does provide some redundancy due to the two strings in parallel. The main disadvantage is the high price compared to the limited output.

Due to the reasonable power output from Configuration E, and the very good price / power ratio this seems an obvious choice. There are, though, two problems before we can choose this arrangement. One is if it is at all possible to purchase the cells from the US. Another important issue is the size constraint. The MEK group is in doubt whether 3 such cells will fit on each of the 5 sides of the satellite due to other payload requirements.

We’ve therefore agreed with MEK and Mogens Blanke, that we’ll purchase a box of the cheapest cells from Spectrolabs with an efficiency >16% and sold with coveralls, in order to see how they can be assembled on the chassis. Also the MEK group would like to see how easily they break - presumable pretty easy, and finally the cells can be used for a display model of the final satellite.

9. Choice of Battery

As we saw in section 3.10 the best suited battery for the satellite is based on Li-Ion technology. Unfortunately it has been difficult to get such a battery because they are not commercially available in small quantities.

Li-Ion batteries that are packed in a cylindrical or prismatic package are to be preferred because they have a structure that is rough and vacuum stable. This is unlike the Li-Ion Polymer cells that are packed in an aluminum foil that is coated with plastic, because it is a cheaper solution.

One possibility of getting a Li-Ion battery pack is to use one sold for cellular phones, camcorders or other handheld devices. These packets contain a battery with a security circuit that will prevent the battery from being over- and undercharged and also prevents it from delivering too high an output current. It is, of course possible to buy a battery pack, disassemble it and hope that it contain a battery that can be used. Unfortunately there is a risk that the battery doesn't contain any specification numbers, so that it is impossible to find a useful datasheet.

We have tried to purchase a cylindrical Li-Ion battery from Sony, which actually happens to be the same kind that is proposed to be used for the next Danish satellite called Rømer, namely Sony's US18650. In the end their legal department advised them against selling us the batteries due to security issues if something went wrong, for instance a battery that exploded.

We have instead received some Li-Ion Polymer batteries from Danionics. We have been vacuum testing them, where they swelled up to about twice their normal thickness, see appendix G for pictures before and during the test. This is, of course not useful for our satellite. Anyway, if they are to be used, they must be packed in some sort of glass fiber or carbon fiber to prevent them from swelling in vacuum, or they must be installed into a small metallic box. For now the Danionics' batteries are fine for testing with the Li-Ion charger because the Li-Ion Polymer and the Li-Ion batteries have the same charge and discharge characteristics.

The charge and discharge characteristics at 25 °C have been measured with the a/d converters connected to ISA card. The result is shown in figure 22. The blue curve is the battery voltage, and the purple one is the current in mA.

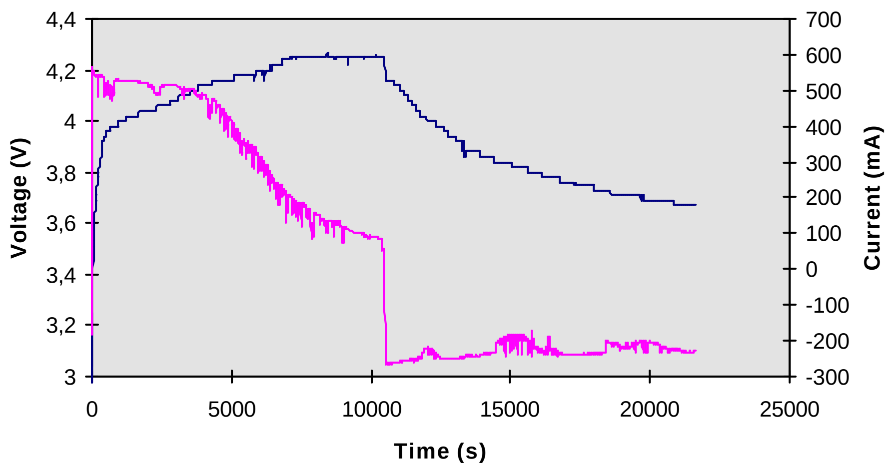


figure 22 - Charge and discharge cycle for the Danionics Li-Ion polymer battery

The curves for both the battery voltage and the current are similar to the ones described in the battery theory section. We can therefore say that the charging circuit works fine.

It can be seen that the curves contains some jumps which is simply measuring errors, these are probably due to the fact that we didn't use a routed PCB for the analog part of the measurements.

10. Battery Chargers

It can be discussed whether or not it is necessary to use a charging circuit to charge the battery, because in a system where there is limited power available a charging circuit adds another power loss. Lessons learned from previous small satellites are that rechargeable batteries should *always* be provided with a protection circuit against overcharging, even if anticipated loads would normally prevent this from occurring [ES95, page 11-34]. Changes in the satellite loads can result in failures or degradation in the battery. Therefore a charging circuit must be used in the DTUsat to ensure that no failure occur.

The choice of battery charger to use is not insignificant. The best charger for the satellite is of course a circuit that can protect the battery against failures and consumes as little power as possible. In the following sections different charger topologies will be studied and the best suited for the DTUsat will be chosen.

10.1 Linear Chargers

This type of charger uses a linear regulator to control the battery current or voltage. The input voltage to the charger must be higher than the battery voltage. A series transistor is more or less open and controls the charging voltage. The voltage across the transistor will be the difference between the input voltage V_{in} and the output voltage V_{out}. This gives a power loss P_{loss} in the transistor, which is V_{in} - V_{out} times the output current I_{out}. This makes the linear charger simple but inefficient.

10.2 Switch Mode Chargers

This type of charger uses a switching regulator to control the battery current or voltage. A series transistor operates as a switch, which is either open or closed. When the transistor is conducting there is only a small voltage drop across it which makes the power loss very low. The transistor is controlled by a periodic signal, and this makes the output voltage a square wave voltage with an amplitude of the same size as the input voltage. The output DC value is controlled by the duty cycle of the periodic signal that is applied to the transistor's gate. By applying a loss less LC-lowpass filter at the output, the final output voltage of the switching regulator is the DC value of the square wave voltage which contain a little AC ripple at the switching frequency.

This makes the switch mode charger a little complex but very efficient.

10.3 Choosing the Best Battery Charger

The best charger is not just the most efficient one, but it also depends on its space characteristic. The efficient but complex switch mode charger is for example more sensitive to single event latch up than the more simple and inefficient linear charger [KF99, page 81-82].

We have used the Max1879 single cell Li-Ion charger to charge the battery. Maxim claims that it features an efficient pulse-charging architecture, that supposedly "combines the efficiency of switch mode chargers with the simplicity of linear chargers".

Max1879 charges 1 cell from an input voltage as low as 4.5V and will restart the charging when the battery voltage falls below 4V. It includes some overcharge protection and a safely precharge mode for near dead cells. A cell that have been exposed to over discharging (to a terminal voltage below 2.0V) is called a near dead cell.

When the input power to the Max1879 is removed, but it is still connected to the battery the battery will discharge through the charger with a maximum battery current drain of 1.5 µA. The operating temperature range is from -40 °C to +85 °C.

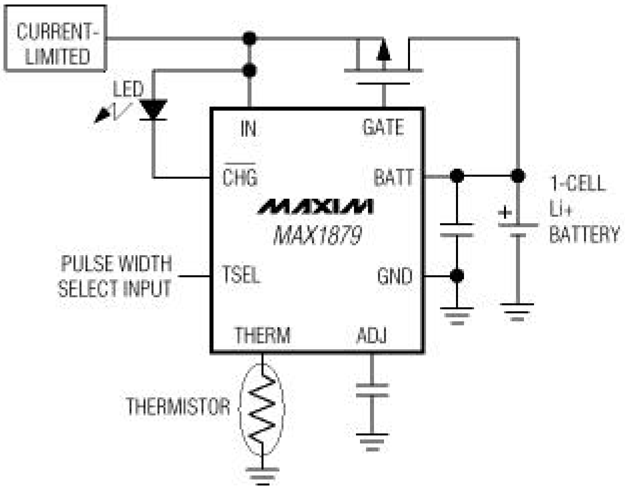


figure 23 - Typical operation circuit for the Max1879 Li charger

The LED is meant as a status indicator to see if the circuit is charging and is not necessary in the final power system, although a pull up resistor can be connected to the open-drain output to generate a logic level signal that can be saved as housekeeping information. The TERM pin is connected to a 10 kΩ resistor, because we don't want to use the internal temperature protection circuit. If temperature sensing is included the charger will only charge a battery in the temperature range +2.5 °C to +47.5 °C and the satellite may need to operate in the temperature range -40 °C to +80 °C.

11. DC/DC Converters

To be able to deliver a stable voltage of 3,3V to the users on the DC-bus, some sort of DC conversion is needed. A DC/DC converter is a device that accepts a DC input voltage and produces a DC output voltage. Typically the output produced is at a different voltage level than the input.

The voltage from the solar panels, while they are illuminated, is 6.1V, but while they are not illuminated their open circuit voltage is 0V and the rechargeable battery has to deliver all the power. This battery voltage will vary between 3,0V and 4,2V, but this does not include a diode voltage drop of 0,4V. Therefore the voltage from the battery will be between 2,6V and 3,8V. As mentioned in the specifications it has been decided that galvanic isolation will not be used.

11.1 Linear Converters

This type of voltage converter must have a higher input voltage than the output voltage.

The linear converter has an internal series transistor that is more or less open and drops the difference between the input and output voltages. The voltage across the transistor will be the difference between the input voltage V_{in} and the output voltage V_{out}. This gives a power loss P_{loss} in the transistor, which is V_{in} - V_{out} times the output current I_{out}.

The linear DC converter is not very efficient, but it has a simple internal structure that makes it a Rad Hard component.

In applications where the regulator runs very close to the output voltage, a linear regulator with a low dropout voltage can deliver more of a battery's energy to a load than a switching regulator. In other words: It is more efficient [BM94, page 59].

11.2 Switch Mode Converters

This type of converter uses a transistor as a switch, which is either open or closed. When the transistor is conducting the voltage drop across it is 0V. This makes the power loss theoretically zero. The transistor is controlled by a periodic signal, and this makes the output voltage a square wave voltage with an amplitude of the same size as the input voltage. The output DC value is controlled by the duty cycle of the periodic signal that is applied to the transistor switch. By applying a loss-less LC-lowpass filter at the output, the final output voltage of the switching regulator is the DC value of the square wave voltage which contains a little AC ripple at the switching frequency.

The advantages of the switching converter are of course its high efficiency and that the output voltage can be either higher or lower than the input voltage depending on the duty cycle. The converter is both step-up and step-down compatible, but the converter is a bit complex due to the switching, and this makes it a Rad Soft component.

Several different types of switch mode topologies exist. To be able to find the best suited topology, the different topologies will be now be studied.

11.2.1 Buck-Boost

In a Buck-Boost converter the output voltage has the opposite polarity of the input voltage. The FET is pulsed with a square wave. The coil stores magnetic energy when the FET is on and when the FET is off the diode is forward biased and the coil deliver it's stored energy to the load. The Buck-Boost converter can run in to different modes:

Continuous conduction mode (CCM), where the coil does not deliver all the stored energy to the load before "new" energy is stored in the coil. This means that current flows in the coil all the time.

In discontinuous conduction mode (DCM) all the stored energy in the coil is delivered to the load before the coil is charged again, and therefore the coil current reach zero in each charge period.

11.2.2 Buck-Boost in Continuous Conduction Mode

The diagram for the Buck-Boost converter in CCM is shown in figure 24. The duty cycle D is the ratio between the on time for the FET and the entire period T. In the time from 0 to DT the FET is on and the coil voltage, v_L, is the same as the input voltage V_{in}.

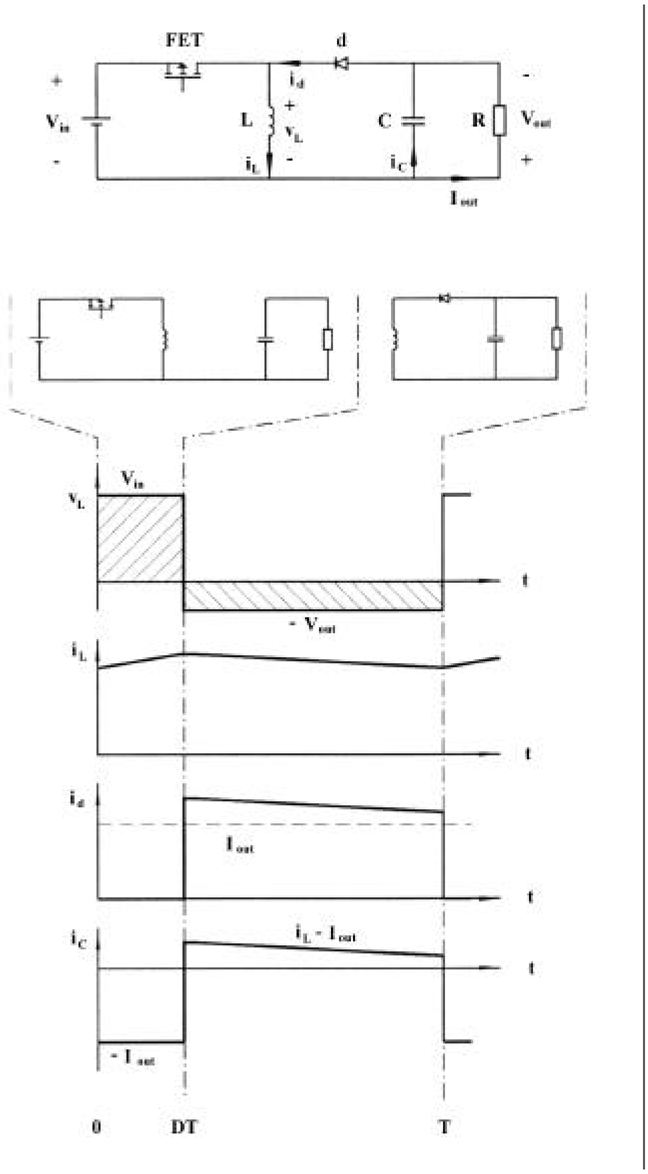


figure 24 - Buck-boost converter in continuous conduction mode

The coil current is determined by

$$v = L\frac{di_L}{dt} \Rightarrow i = \frac{1}{L}\int v_L(t)\,dt$$

Hence the coil current will increase linearly with time.

The diode d is blocking, $i_d = 0$, and the load current is delivered by the capacitor C and hence $I_{out} = -I_C$.

In the time interval from DT to T where the FET is off the diode conducts and if the diode voltage drop is neglected, the coil voltage will be $v_L = -V_{out}$.

The diode current $i_d = i_L = i_C + I_{out} \Rightarrow i_C = i_L - I_{out}$.

The capacitor current has a momentum jump greater than the output current between each of the FET's on and off intervals. Unfortunately these jumps cause a great deal of AC ripple on the output. An increase in the output current causes an increase in the AC ripple, so the Buck-Boost converter is not suited for high output currents.

The coil current must be the same at the start of each period, otherwise the coil current will increase toward infinity or decrease toward minus infinity.
Hence the coil current over one period must be equal to zero.

$$\Delta i_L = \frac{1}{L}\int_0^T v_L(t)dt = 0$$

And the average of the coil voltage over one period must also equal zero.

$$v_{L,average} = \frac{1}{T}\int_0^T v_L(t)dt = 0$$

The above expression for the coil voltage shows that the two shaded areas on figure 24 must be equal and hence

$$V_{in} * DT = V_{out}(1-D)T \qquad \Rightarrow \qquad \frac{V_{in}}{V_{out}} = \frac{D}{1-D}$$

As seen from the above transfer function the Buck-Boost converter can produce a step down function if the duty cycle is less than 0,5 and a step up function if the duty cycle is greater than 0,5.

11.2.3 Buck-Boost in Discontinuous Conduction Mode

The diagram for the Buck-Boost converter in DCM is shown in figure 25. In the time interval from 0 to DT, $v_L = V_{in}$, $i_d = 0$, and $i_C = I_{out}$ for the same reasons as mentioned for CCM. At time 0 the coil current is zero and it rises linearly until time DT where it has the magnitude i_{max}.

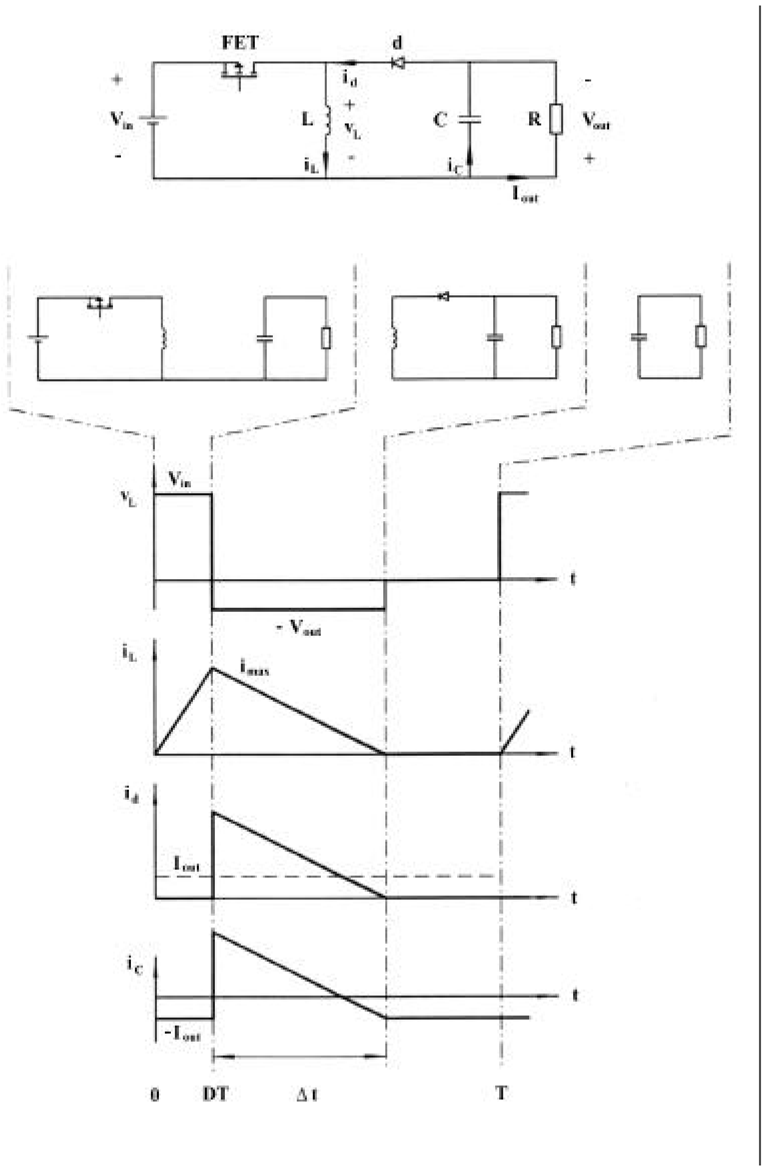


figure 25 - Buck boost in discontinuous conduction mode

In the time interval Δt the coil current i_L decreases linearly through the diode $i_d = i_L$, and the coil voltage $v_L = -V_{out}$. The capacitor current is given by $i_C = i_L - I_{out}$.
At time DT + Δt the coil current reaches $i_L = 0$, and for the rest of the period the diode is blocking and the capacitor provides the load current.

It is easier to find the output voltage in DCM by using energy calculations. The stored energy in the coil is at time DT given by

$$W_L = ½\, L\,(i_{max})^2$$

If there are no losses in the converter all the stored energy in the coil is delivered to the load. Power is defined as energy per time so the power consumed by the load is

$$P_{load} = \frac{W_L}{T} = \frac{L\,(i_{max})^2}{2T} = \frac{(V_{out})^2}{R} \quad \Rightarrow \quad V_{out} = i_{max}\sqrt{\frac{RL}{2T}}$$

The output voltage V_{out} is dependent on the load resistance. In the DTUsat the load will differ from time to time and therefore it will be too difficult to use a Buck-Boost converter in DCM.

11.2.4 Buck Converter

The Buck converter and its waveforms for voltages and currents is shown in figure 26, but only in CCM because for DCM the output voltage also depends on the load resistance.

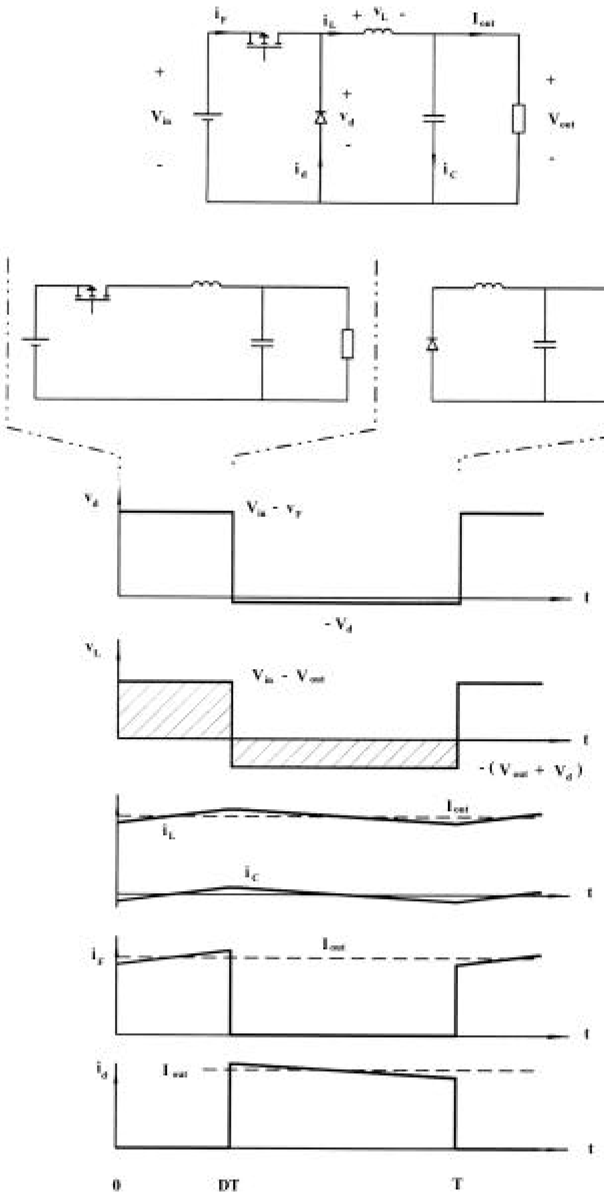


figure 26 - Buck converter

The analysis is similar to the Buck- boost so only the transfer function will be given:

$$\frac{V_{out}}{V_{in}} = D, \qquad 0 \leq D \leq 1$$

It can be seen that the Buck converter only can produce an output voltage smaller than the input voltage.

11.2.5 Boost Converter

The Boost converter and its waveforms for voltages and currents is shown in figure 27, but only in CCM because for DCM the output voltage depends on the load resistance.

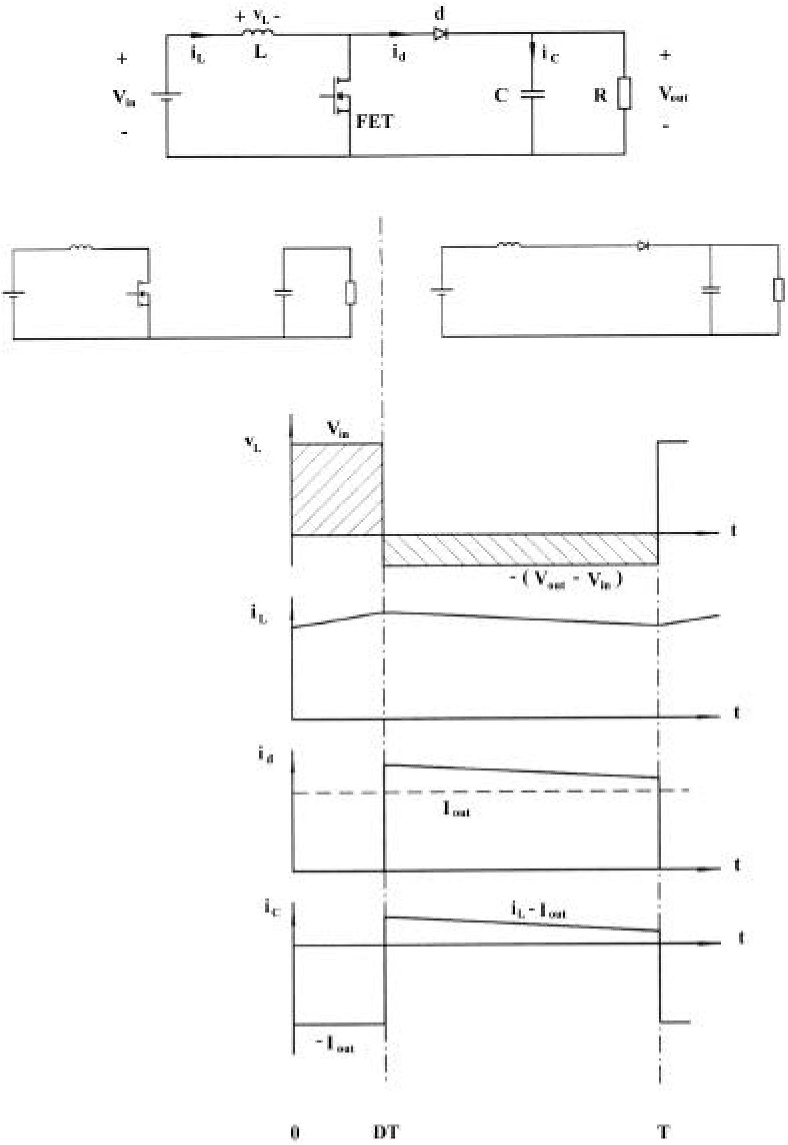


figure 27 - Boost converter

Here the two shaded areas has to be equal so like before the transfer function can be can be found as

$$V_{in}\, DT = (V_{out} - V_{in})(1-D)T \quad \Rightarrow \quad \frac{V_{in}}{V_{out}} = \frac{1}{1-D}$$

The Boost converter can only produce an output voltage that is higher than the input.

11.3 Converter Comparison

The system engineering group has decided that the load voltage must be kept stable at 3.3V DC. The amount of AC noise that the load voltage is allowed to have is not decided yet.

The linear regulators can only step down the input voltage and it need a higher input voltage than the output voltage it produces. Even if we choose a linear regulator with a low dropout voltage (about 0.4V) the battery voltage while discharging is not allowed to vary much before the regulator will have a too low input voltage to work properly. If the battery temperature is low it cannot provide a sufficient voltage and the regulator will not work at all. Hence the linear regulator is unsuited even though it is more Rad Hard than the switching regulators.

The voltage ratios achievable by the different topologies of switching DC/DC converters is summarized in figure 28. Only the buck converter shows a linear relationship between the duty cycle and output voltage.

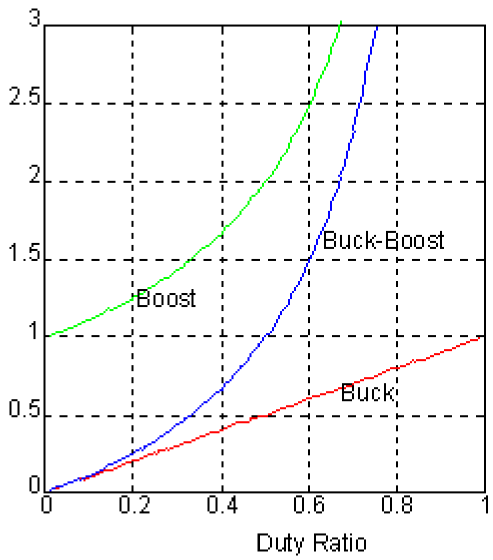


figure 28 - Duty cycles vs. voltage ratios for switching DC/DC converters

The most suited topology of the switching converter is the Buck-boost converter because of its capability to perform both a step up and a step down function. This converter will produce a stable output voltage almost independent of the input. The Buck-Boost do need a controlling circuit that can set the needed duty cycle dependent of the input voltage. If the efficiency can be made high enough without making the converter too complex, this converter type will properly be the best suited.

The Buck converter that has the property to step down the input voltage can also be used. This type of converter can only work if the input voltage is higher than the output voltage of 3.3V. Hence it will not work if the battery voltage falls below the minimum input voltage plus the battery diode voltage drop, 3.4V + 0.4V = 3.8V. But if the Li-Ion battery have a very low DOD there may be a change for the Buck converter to work properly to satisfy the need for a stable load voltage of 3.3V DC. The only problem is that the battery voltage may drop due to a low temperature. The buck converter also requires a regulator to control the duty cycle.

The Boost converter is not suited because it can only transform the input to a higher voltage and the solar cell voltage will under normal operation always have a higher output voltage than the specified load voltage. The Camera payload group have talked about a camera that may require 5V. And Hence the Boost converter may be needed after all.

11.4 The Max1626 DC/DC converter

The Max1626 is a step down DC/DC converter that is used to provide a regulated load voltage of 3.3V with a input that varies between 3.4V and 16.5V. The converter uses a Buck topology to transform the input voltage. The maximum quiescent current is 90µA and the maximum shutdown current is 1µA.

The values of the external components used are the ones proposed in the datasheet. These are shown in the figure below:

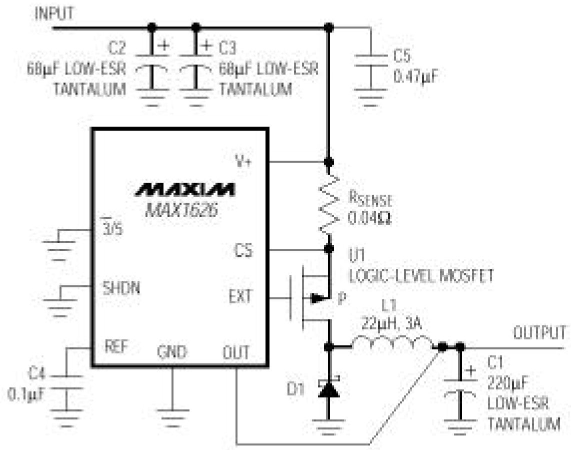


figure 29 - Typical application circuit for Max1626

The datasheet promises an efficiency of more than 90% for an input voltage of 4.3V, an output voltage of 3.3V and load currents between 3mA and 2A. We achieved the efficiencies shown in the following figure:

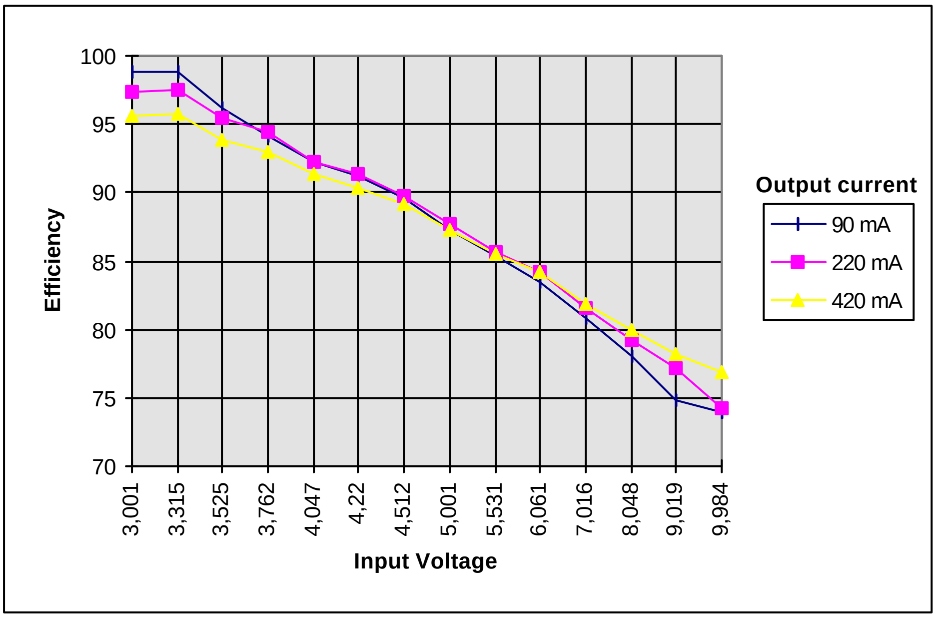


figure 30 - Efficiency test of Max1626

The efficiencies that we measured for the Max1626 were about the same as the promised ones. It should be noted that the converter isn't working properly with an input voltage below 3.4V and therefore the very high efficiencies we measured for the input voltages below 3.4V can only be achieve because the only losses are in the 40 mΩ resistor and the on resistance of the MOSFET.

12. Latch Up Protection

As described in section 4.2 latch ups can be neutralized by turning off the power from the affected circuit. To do this we need to detect that a latch up occurs. This can be done by measuring the current drawn by the circuit. Because some parts of the satellite use many orders more power than others, we can't use the total current drawn by the satellite systems as a hole as a measure. We must therefore monitor the individual subsystems.

We will use the Maxim 890 current limited high-side switch for this purpose. See figure 31 for a typical operating circuit. The chip operates from +2,7V to +5,5V, and the quiescent supply current is less than 20 µA. It can limit the current drawn from the load, this is set by an external resistor, also the output is short circuit protected. The maximum current limit is 1,2 A which is sufficient for every subsystem in the satellite. This limit is set using the formula:

$$R_{Set} = \frac{1380}{I_{Limit}}$$

When the chip is limiting the current on the output, it lowers an open-drain $\overline{\text{Fault}}$ signal. This signal can then be wired together with several other 890 chips and be used to turn off the entire satellite for 1 to 5 seconds. Also the 890 chip features an on/off signal that can be used by the OBC to turn on/off the individual subsystem.

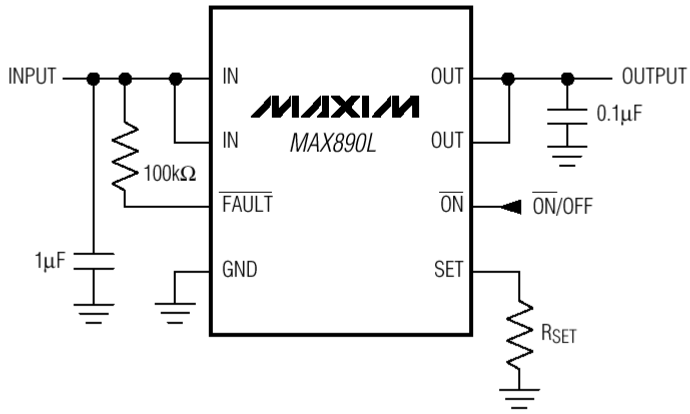


figure 31 - Typical operating circuit of the Max890

Whether the latch up protection should be physically located on the power supply's board (each system gets it's own dedicated power line) or on the individual subsystems boards (all systems share a common power line) was discussed on some of the system engineering meetings. In the end it was agreed that the best method would be to locate the protection on the individual subsystems boards.

In the beginning of the project we considered only switching the power for the subsystem that was latching up. The general feeling in the system engineering group was that this would cause too many problems because the system might be in the middle of a steam of communication with the OBC. It was therefore agreed to switch the power for the entire satellite whenever a latch up occurs.

13. Interface to the Onboard Computer

Because we only considered shutting down the individual subsystem that caused the fault in the beginning of the project, we could set a bit, that later could be read by the OBC in order to see what subsystem caused the latch up. This would allow the software to see if one system did latch up more often than others, which could be useful information for a later mission.

It turned out, that this approach required way too much overhead, both considering registers, and communication wires to the OBC. This approach was therefore abandoned and a simpler one developed, which is described in the previous section.

Other information that must be transferred to the OBC includes house keeping data. The system engineering group has decided that the following values should be monitored:

- Currents from each solar array (5),
- Common voltage for solar arrays,
- Battery voltage,
- Current to/from the battery,
- The common DC bus voltage,
- The current drawn at the common DC bus, and
- The temperature of the battery

It has not yet been decided how often these numbers should be sampled, nor to what accuracy. The temperature will most likely be measured by a one-wire system. Since we need to sample altogether 10 currents and voltages it has been decided that the a/d converters should be located on the power system's circuit board. The data is then transferred to the OBC over an SPI bus. The choice of a/d converters for this task has not yet been investigated.

The current interface description for DTUsat can be seen in appendix B.

14. Radiation Tests

14.1 Total Dose Radiation Test

To test whether or not the integrated circuits are suited for space applications a total radiation dose test is needed. Such a test was performed at Risø in order to give an idea of how the components will react to these long term effects. At Risø the components were exposed to different amounts of radiation, namely: 0.897 krad, 1.794 krad, and 4.484 krad. The tests were performed at a dose rate of 25.05 rad/s.

The amount of total dose radiation that the DTUsat can expect in one year is about 1 to 2 krad and hence tests at the above radiation levels should give a good indication on whether or not the components can be used.

The components have not been tested before they were exposed to radiation, but they were taken from the same batch, and a sample from each batch that had not been exposed was also tested. All tests for the same type of components have been made using the same evaluation board so the external components were the same.

At the present time we do not have any sockets for the ICs, so unfortunately they had to be soldered. This is not an optimal solution because it is impossible to say if it is due to the radiation dose or a too high soldering temperature, if they don't work. Because of that we chose only to test one component type, namely the Max890, at one level of radiation and wait for further tests until we get some sockets, which btw. has been ordered.

14.1.1 Max890

First a sample that was not exposed to radiation was tested. This was done because we needed to have something to relate the results of the radiation exposed components to.

The results of the electrical characteristics tested are shown in appendix H. Because we haven't got the sockets yet, we chose only to test at one level of radiation. The sample that was exposed to 4.484 krad was chosen because we expected to see the highest changes in the values for this one.

As can be seen from the table in appendix H the characteristics did not seem to have changed significantly.

14.2 Latch Up Test

Until now we haven't had the opportunity to test for latch up conditions. At some time when the engineering model of the satellite is ready we will be able to perform such a test on the entire satellite at a facility at Rigshospitalet.

14.2.1 Max890

Kurt E. Forslund at Alcatel Denmark has helped us examine the functional diagram of the Max890, which can be seen in appendix H. It does not seem to contain digital elements that may be the reason for a permanent shutdown. On the other hand there is a change of a temporary shutdown if a transient occurs at one of the amplifier outputs. These shutdowns will probably be limited to < 40 μs, after which the output will operate normally again. This can be solved by placing a capacitor on the output terminal. The frequency of these temporary shutdowns is impossible to say, but an expected rate will most likely be less than one per day, even under high solar activity.

As is true for any CMOS circuit a MOSFET may be destroyed by a latch up in one of the digital or analog circuits. This risk is impossible to evaluate, partly because the technology used is unknown. This is also common to all other COTS components.

15. Conclusions

This ends our design considerations for the power supply. During this project we have studied several battery technologies, solar cells, and converter topologies. Furthermore the harsh environment of space has been described. The choices for solar cells and battery capacities are based on a discussion and feasibility study of the power budget which has been set up after many discussions with the other groups involved in the DTUsat project.

The power supply is far from complete. We will now sum up the parts we have finished, and the parts we haven't. Even though the list of unfinished problems seems rather long it should be noted that most of the issues has been partly solved. We therefore don't see any reason why we shouldn't have a final engineering model of the power supply ready by the summer 2002.

15.1 Results

The design of the solar arrays have been finished, and the solar cells have been ordered. Also the best kind of battery chemistry suited for the DTUsat has been found. It was found to be a Li-Ion cylindrical cell with a capacity of about 1500 mAh.

As the power calculations show, the current power budget seems feasible. For a battery with a capacity of 1500 mAh a DOD of at most 10%, and of an average of 5% is achieved. Because of this we expect a Li-Ion battery to last for about 10.000 cycles which is sufficiently for almost 2 years of operation.

Also the power calculations showed that it is possible to completely recharge the battery in a single orbit after a transmission has been made without solar power.

Different topologies of the electrical power system has been considered and the best one has been chosen. The consequences of battery operating at low temperature has been discussed. In order to get a stable load voltage, no matter what happens, it has been shown that a DC-DC converter that can perform both step up and step down functionality is required. This is due to the reason that the voltage of the battery may vary from a voltage lower than the regulated bus to a value somewhat higher than the regulated bus.

15.2 Future Work

A. General:

- A Li-Ion battery that is packed in a cylindrical package must be purchased, for instance Sony US18650.
- Otherwise a method to protect the Danionics battery from vacuum must be invented.

B. Design:

- The maximum allowable noise on the output has to be determined by talks with the other groups of the project, until now we can only design the system with as little noise as possible without knowing whether this is good enough or not.
- A latch up protection circuit in discreet technology is to be designed. It must have the ability to shut down the entire satellite if a single event latch up occur.
- Thermal calculations must be made so we get an idea about how cold the battery might become and also check if the components can dissipate the heat generated.
- The overall efficiency for the power supply must be optimized in the final design.

C. Testing

- A long term vacuum battery charge/discharge test where the temperature varies in the interval which the battery will experience in space must be done. This is necessary because we need to be certain that the battery will work in space.
- All the components we use must be exposed to a total dose radiation test so the long term changes are known and so that we get a picture of how much radiation we can expect each component to be able to withstand.
- The power supply unit, along with the other subsystems, must be exposed to high energy particles so it can be seen if the latch up protection circuitry works.
- If time allow simulations with a satellite model that has body mounted solar cells will be done in order to simulate the satellite in orbit.

15.3 Conclusion

The reason that a project like DTUsat is interesting also turned out to be one of the greatest challenges: To be part of a large project requires a lot of communication and coordination between the different groups. For instance weight budgets and power budgets must be agreed, but also pictures for posters, and short descriptions for applications for financial support applications had to be made.

Because no one at DTU, or even in Denmark, had tried to work on a similar project, everybody, including most of the supervisors, were starting from scratch. This was both a relief, a source of enthusiasm, and a cause of many frustrations, because it meant that it wasn't always possible to find someone that could help with a certain problem. But as an engineering student it feels great to be part of a project that is operating at the edge of the present technology. This easily outweighs the problems.

It was obvious from the beginning that this project wasn't a usual one, where you get some design specifications, write some theory about possible solutions, design and simulates a chosen solution, and eventually builds it to see if everything works out in the end.

The one reason that this project is different is plain and simply because: *The design specifications didn't exist* - we had to make them ourselves together with the other groups in the project. This includes everything from deciding the payloads, over weight budgets to determine the timeline in order to get a finished product ready for delivery in time for the launch.

This part, designing the specifications, turned out to take a lot of time - almost two months went by before we had some reasonable data that allowed us to begin to make our own assumptions like battery capacity, and solar string voltage. Only two weeks ago the first feasible interface description between the individual subsystems were made, and the process is still not complete - a method for connecting the subsystems has, for instance, not yet been decided.

We do, however, think that the effort has paid out well, and that we are better prepared for similar projects in the 'real world' than many other students.

We also believe that one of the most important skills for an engineer is to be able to study new technologies, and afterwards use this information for designing a new system. This has especially been true for this project as neither of us new anything about solar cells, lithium ion batteries, or the harsh environment present behind the protective atmosphere of the earth.

16. References and Literature

16.1 References

[BM94] Bruce D. Moore: Regulator Topologies Standardize Battery-Powered Systems, EDN, January 20, 1994

[BT01] Bob Twiggs and Jordi Puig-Suari:
Cubesat Design Specifications Document, Revision 5, November 2001
http://ssdl.stanford.edu/cubesat/specs-1_files/CubeSat%20Developer%20Specifications.pdf

[CK98] Chad O. Kelly, H. Dwayne Friend, and Casey A. Keen:
Lithium-Ion Satellite Cell Development: Past, Present and Future,
IEEE AES Systems Magazine, June 1998.

[DL95] David Linden: Handbook of batteries, 2nd edition,
Mcgraw-Hill Book Company Inc., 1995

[ES95] Edward M. Silverman, Space Environmental Effects On Spacecraft: LEO Materials Selection Guide - Part 2, NASA, August 1995
http://techreports.larc.nasa.gov/ltrs/PDF/NASA-95-cr4661pt2.pdf

[GC97] Gunnar Christiansen, Erik Both, Preben Østergaard Sørensen:
Mekanik, DTU, 1997

[GE97] G. M. Ehrlich, R. M. Hellen, and T. B. Reddy:
Prismatic Cell Lithium-Ion Battery Using Lithium Manganese Oxide, IEEE 97

[HH00] Hank Heidt, Jordi Ruig-Suari among others:
Cubesat: A new Generation of Picosatellite for Education,
14th Annual/USU Conference on Small Satellites, 2000

[HR80] H. S. Rauschenbach: Solar Cell Array Design Handbook,
Van Nostrand Reinhold Company, 1980, ISBN 0-442-26842-4

[IB00] Isidor Buchmann: A Lion's share of the future;
Meeting report: Batteries international, January 2000.

[IB01] Isidor Buchmann: The Li-Polymer battery: substance or hype?,
Cadex Electronics Inc., April 2001

[JP01] Yuichi Tsuda, Nobutada Sako and others:
University of Tokyo's Cubesat Project, 2001

[JW99] James R. Wertz, and Wiley J. Larson: Space Mission Analysis and Design,
Microcosm Press, 1999, ISBN 1-881883-10-8

[KF99] Kurt E. Forslund, Danish Small satellite Programme:
Study of electronic components for small satellites, Alcatel, 1999-11-05
http://www.dsri.dk/roemer/pub/Documents/ECSS_1F.PDF

[MX01] Maxim application note: System-Level Issues in Applying Battery-Charger ICs,
http://dbserv.maxim-ic.com/appnotes.cfm?appnote_number=680

[MX02] Maxim application note: Versatile ICs Enable Chemistry-Independent Battery Charging
http://dbserv.maxim-ic.com/appnotes.cfm?appnote_number=666

[NA01] M.C. Smart, B.V. Ratnakumar, among others:
Performance Characteristics of Li-Ion Cells for NASA's Mars 2001 Lander,
IEEE AES Systems Magazine, Nov. 1999

[WK01] Walt Kester and Joe Buxton: Battery Chargers, Section 5, Analog Devices,
http://www.analog.com/technology/powerSupervisoryInterface/training/pdf/fsect5.pdf

[WP78] Wolfgang Palz: Solar Electricity,
Butterworths, UNESCO, 1978, ISBN 0-408-70910-3

16.2 Links to Websites

[SP00] The Spenvis Homepage
http://www.oma.be/spenvis

[PI00] NASA: Pioneer Project Home Page
http://spaceprojects.arc.nasa.gov/Space_Projects/pioneer/PNhome.html

[VO00] NASA: Voyager Project Home Page
http://vraptor.jpl.nasa.gov/voyager/voyager.html

16.3 Secondary Literature

Batteries:

David Linden: Handbook of batteries, 2nd edition
Mcgraw-Hill Book Company Inc., 1995,

Solar Cells:

Martin A. Green: Solar Cells,
Prentice-Hall, 1982, ISBN 0-13-822270-3

H. S. Rauschenbach: Solar Cell Array Design Handbook,
Van Nostrand Reinhold Company, 1980, ISBN 0-442-26842-4

DC/DC Converters:
Michael A.E. Andersen, Arne Hansen, Henrik Havemann, and Jørgen Kaas Pedersen:
Grundlæggende effektelektronik, DTU, 1997.

Mohan, Undeland, and Robbins:
Power Electronics, Converters, Applications and Design, 2nd Edition, Wiley, 1995

Robert W. Erickson, and Dragon Maksimovic:
Fundamentals of Power Electronics, 2nd edition, Kluwer Academic Publishers, 1999

Space Environment:
Kurt E. Forslund, Danish Small Satellite Programme:
Study of electronic components for small satellites, Alcatel, 1999-11-05
http://www.dsri.dk/roemer/pub/Documents/ECSS_1F.PDF

Edward M. Silverman, Space Environmental Effects on Spacecraft:
LEO Materials Selection Guide Part 1 and 2, NASA, August 1995
Part 1: http://techreports.larc.nasa.gov/ltrs/PDF/NASA-95-cr4661pt1.pdf
Part 2: http://techreports.larc.nasa.gov/ltrs/PDF/NASA-95-cr4661pt2.pdf

16.4 Datasheets

Max472 http://dbserv.maxim-ic.com/quick_view2.cfm?qv_pk=1108

Max890 http://dbserv.maxim-ic.com/quick_view2.cfm?qv_pk=1526

Max1626 http://dbserv.maxim-ic.com/quick_view2.cfm?qv_pk=1236

Max1879 http://dbserv.maxim-ic.com/quick_view2.cfm?qv_pk=2544

Sony Batteries, particular US18650:
http://www.sony.co.jp/en/Products/BAT/ION/Catalog-e.pdf

Appendix A - Cubesat Specification Drawing

1 page

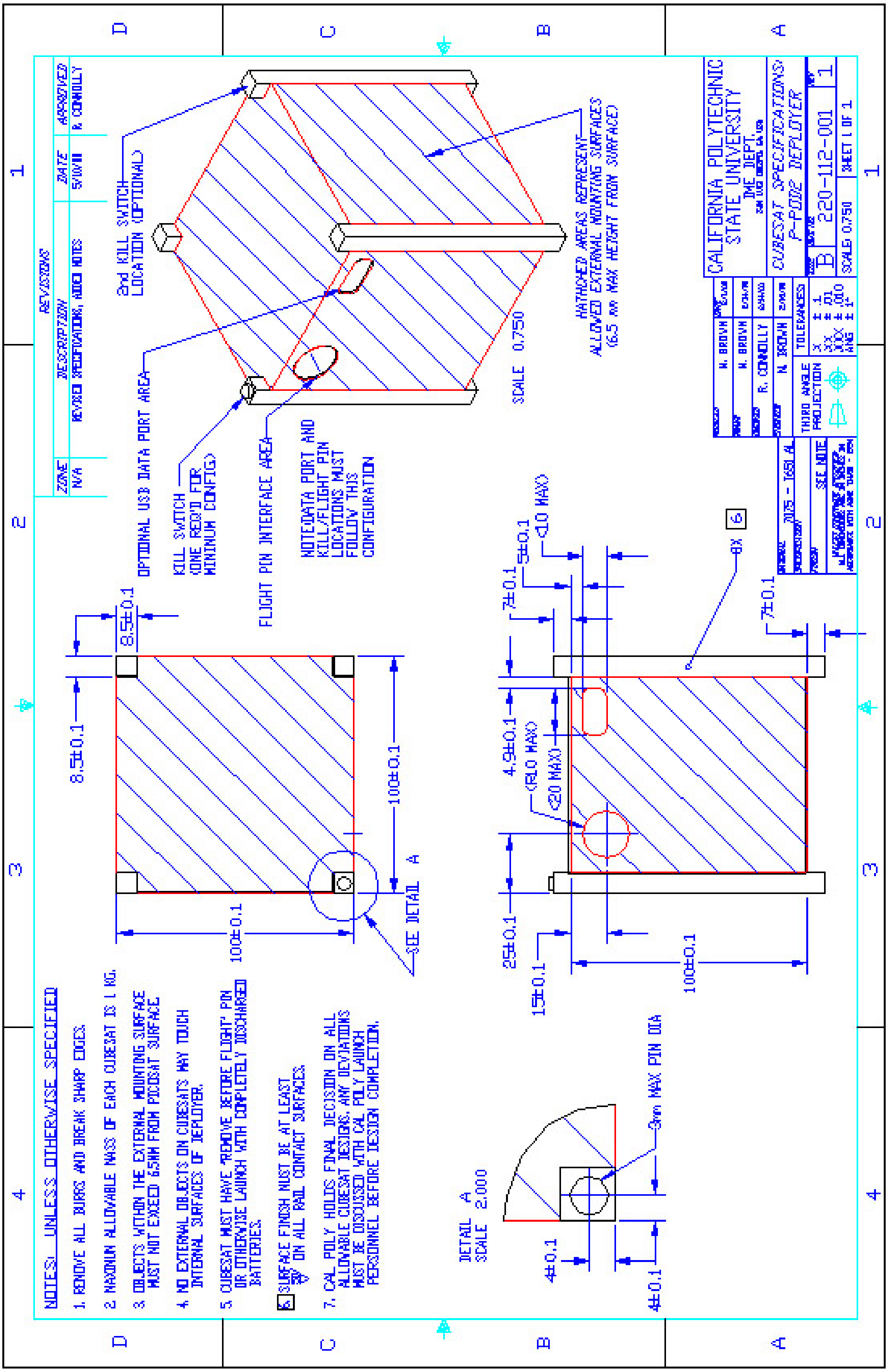


Figure 3 - CubeSat specification drawing.

Appendix B - DTUsat Interface Overview

1 page

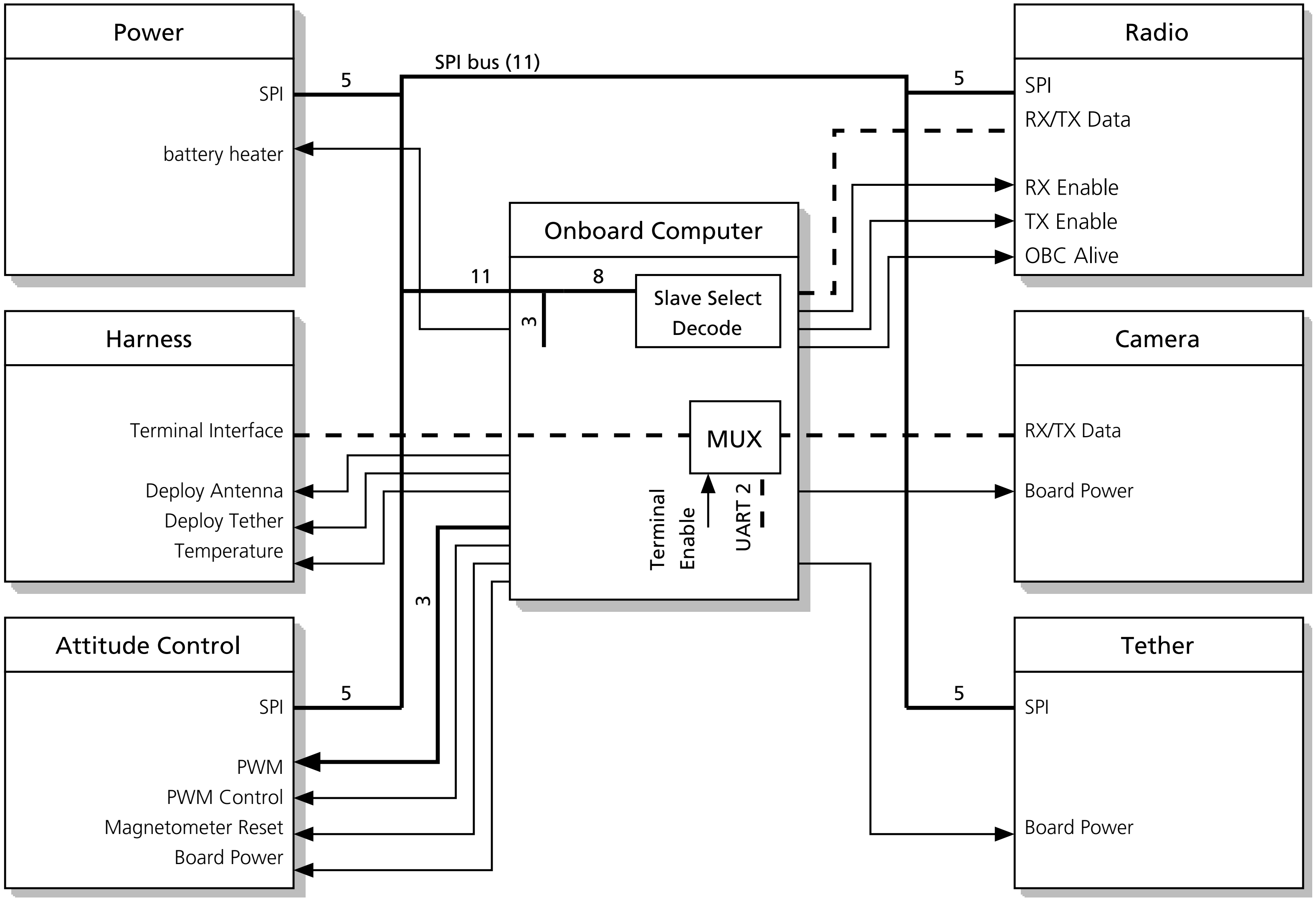


Figure 1: Block diagram of the boards showing their communication interconnections

Appendix C - DTUsat Weight Budget

2 pages

DTUsat vægtbudget pr. 6/02/2002

System		Min vægt	Max vægt	Sandsynlig vægt	Bemærkninger
Struktur, (kasse;-)					
	Paneler	111	150	140	AutoCad beregning
	Hjørnestolper	70	120	75	AutoCad beregning
	Fjeder til udskydning	3	10	4	Vi skal bruge en bestemt fjeder.... Som rent faktisk er ret lille :-)
	Lim/Skruer	10	30	25	Gæt
	Holdere til ACDS, PCB, ETC.	50	120	80	Ingen deciderede holdere til tether og kamera.
	Samlet:	**244**	**430**	**324**	
Backplane					Ukendt, da metode endnu ikke er fastlagt
	Ledinger	20	50	50	
	Stik	20	50	30	
	ETC.	20	50	40	
	Samlet:	**60**	**150**	**120**	
Power, print					
	Printplade	10	15	13	
	Komponenter	15	40	25	
	Thermisk design	5	9	4	
	Samlet:	**30**	**64**	**42**	
				27	
Power					
	Solpaneler incl. Glasfront	60	100	80	Regnet som 6 paneler på 5 sider á 1.5x40x20 i glas
	Killswitche	10	30	15	
	Flight pin	10	20	15	
	Test plug	10	20	15	
	Batterier	40	100	70	Min vægt: 1 Li-ion batteri
					Sandsynlig vægt: 1 Danionics batteri + indpakning, eller 2 stk Li-batterier
					Max vægt: 2 stk Danionics batteri + indpakning
	Samlet:	**130**	**270**	**195**	
OBC, print					
	Printplade	10	15	13	
	Komponenter	5	15	10	
	Thermisk design	5	9	5	
	Samlet:	**20**	**39**	**28**	

ACDS, print					
	magnetorquers	10	50	35	Bør snarest fastlægges ved et praktisk forsøg, også for at få klarlagt montage
	Solsensorer	6	15	12	
	Printplade	10	10	13	
	Komponenter	5	15	10	
	Thermisk design	5	9	5	
	Samlet:	**36**	**99**	**75**	
Radio, print					
	Printplade	10	15	13	
	Komponenter	5	15	10	
	Thermisk design	5	9	5	
	Samlet:	**20**	**39**	**28**	
Antenne					
	Selve antennerne	20	50	40	
	Holdere til antenner	4	30	10	
	Antenne, fødenetværk	15	50	40	
	Mekanisme til frigørelse	10	50	30	
	Samlet:	**49**	**180**	**120**	
Kamera, incl. holder					
	Elektronik	10	20	15	
	Optik mm.	5	20	15	
	Holder	5	20	15	
	Samlet:	**20**	**60**	**45**	Er alt for lav hvis kameraet skal bære egen elektronik
Tether, incl holder					Designvægt er 100g. Dette tilpasses ved at variere i selve tetherens størrelse.
	Tetherholder	10	20	15	Jeg har indført forskellige estimater for Min/Max/Forventede masser.
	Tether	70	35	60	Vægten af emitter og strømforsyning er ret sikre, mens elektronik ikke er.
	Electronik	10	20	15	Jo mindre de andre vægte bliver, jo længere/solidere kan selve tetheren blive.
	Strømforsyning	5	15	5	Som worst-case eksemplet viser, så ville det være rart hvis den samlede
	Electronemitter	5	10	5	design-vægt kunne være over 100g! Den oprindelige plan for tetheren var
	Samlet:	**100**	**100**	**100**	nøjagtig worst-case eksemplet med 200g total: 135g tether, 65 for alt andet....
Samlet:		**709**	**1431**	**1077**	

Appendix D - ISA Data Acquisition Card

9 pages

Appendix D - Description of the ISA Data Acquisition Card

The Schematic and PCB layout files can be found as Protel 99SE files on the http://dtusat.dtu.dk website. You can download a 30-days trial version of Protel 99SE from http://www.protel.com.

Some of our graphs required a huge amount of measurements over a long time (several hours). This seemed impossible to do manually, and therefore we decided to use two a/d converters (Max7821) and a current sense amplifier (Max472). The a/d converters were connected to a parallel port on a PC.

Due to several reasons, two being lack of i/o pins on the parallel port, and another being that we realized that it was rather easy to design an ISA-extension card for a PC we decided to create such a card instead. Two benefits of designing such a card are the possibility to use it in future projects, and that every PC that is a couple of years old supports ISA. It is fine that the PC isn't state of the art, because we don't need a fast computer for our task. One drawback is that ISA-slots tends to be removed from current PC's and it might therefore become difficult to find a suitable computer in a couple of years.

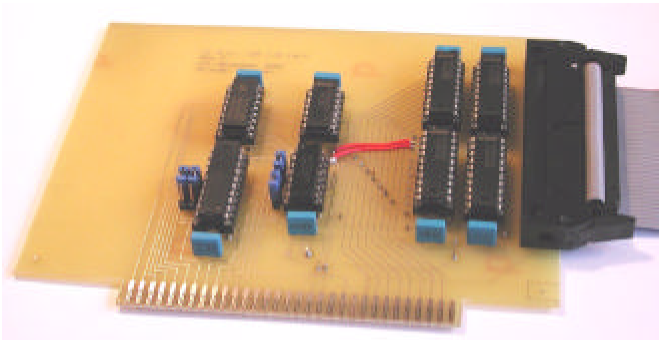


Figure D.1 - The ISA data acquisition card

Address Decoding

The address decoding is made by a 74138 and a 74520. The 74520 takes care of address bit 3 to 10 (only the lower 11 bits of the 16 bit address bus is being decoded on ISA cards). Using two jumpers the base address can be set to 300h, 310h, 320h, or 330h. This prevents resource conflicts, and allows several cards to be used in the same computer.

The '138 receives the equal signal from the '520 and decodes the lower 3 bits into local chip select signals on the board. Two of these are combined with the io-read and io-write signals from the ISA bus and are used to generate output enable and latch enable signals for our 74574 registers. This allows the computer to read and write to our registers on the board.

In order for the external components to write into the registers we need them to set the latch enable signal. Since exact timing of this kind of event might not be needed, and since it, most likely, requires additional logic on the external part we decided to use two extra chip select signals from the '138 to enable the external latch enable signals. Therefore you can store input values in the registers by addressing (read or write) the register address + 4:

	read	write
base address	reads data stored in input register 1	writes to output register 1
base address+1	reads data stored in input register 2	writes to output register 2
base address+4	store external data in input register 1	store external data in input register 1
base address+5	store external data in input register 2	store external data in input register 2

Timing

The normal speed of the ISA bus is 8 MHz, but some systems use clock periods from anywhere between 4,77 to 16 MHz. This doesn't really matter since ordinary 74Fxx and 74ACTxx chips are fast enough even for 16 MHz operation:

One clock cycle is $\frac{1}{16\ \text{MHz}} = 62{,}5\ \text{ns}$. We have 5 levels of logic, each level is thus allowed 12,5 ns, which is fulfilled by both 74Fxx and 74ATCxx chips. You can consequently choose whatever is at hand - or cheaper.

Circuit Diagrams

The circuit diagram for the ISA card can be found on the http://dtusat.dtu.dk website in Protel 99SE format. You can download a 30-days trial version of Protel 99SE from http://www.protel.com.

The schematic for the A/D converters along with the MAX1879 Li battery charger and MAX890 switches can also be found on the website. Together with the following program this configuration allows us to run a number of battery cycles like charge - 5 minutes break - discharge - 5 minutes break - etc.

We can also create a program that simulates the orbit, as in 35 minutes discharge - 63 minutes charge. By adding another 890 we can even simulate the heavy load when transmitting and the softer load when not transmitting.

Example Program

We're using the following program to sample the voltage and current. Data is saved in a @-separated file, which is later imported into Microsoft Excel for creation of plots.

```
program testisa;

{ Created with Borland Pascal 7 }
{ Calibrated for 5V external power supply

  Outputs (CMD):
   0: low: Select ADx
   1:      Sample ADx
   2: low: Select ADy
   3:      Sample ADy
   4: low: Charge On
   5: low: Discharge On }

uses
  crt, dos;

procedure ShortDelay(Interval: Word); assembler;
{ Replacement routine for broken Borland Pascal delay }
{ Interval = number of ticks
```

```
  Note: About 1193180 ticks/s }
asm
  push ax
  push bx
  cmp  Interval,$FFFF   { otherwise $FFFF will end in an infinite loop }
  jne  @begin
  dec  Interval
@begin:
  in   al,040h          { save initial time in bx }
  mov  bl,al
  in   al,040h
  mov  bh,al
@delayloop:
  in   al,040h          { get current time }
  xchg al,ah
  in   al,040h
  xchg al,ah
  sub  ax,bx            { calculate the difference }
  neg  ax
  cmp  ax,Interval      { are we done? }
  jb   @delayloop
  pop  bx
  pop  ax
end;

procedure delay(ms: Word);
var
  A : Word;
begin
  for A := 1 to ms do
    ShortDelay(2386);  { pause for 1 ms, (why not 1193 ???) }
end;

function gettid: longint;
{ returns current time in seconds }
var
  h, m, s, hund : word;
begin
  GetTime(h,m,s,hund);
  gettid := longint(h)*3600+longint(m)*60+longint(s);
end;

function lz(i: integer):string;
var
 S: string;
begin
 Str(I, S);
 if i < 10 then
   insert('0',s,1);
 lz := S;
end;

const
  base = $340;
  antal = 500;
  str : string = '|/-\';

var
```

```
  a, cmd, info : byte;
  key : char;
  buf1, buf2 : array[0..antal] of byte;
  hi, lo,q,b,c,r : word;
  z : longint;
  volt, amp : real;
  sNr, Sign : byte;
  auto, mode : byte; { 0 = off, 1 = charging, 2 = discharging, 3 = auto,
                     4,5 = pause }
  t : text;
  tid,starttid,delta,autostart : longint;

begin
  port[base] := $FF;   { => no A/D's selected }
  port[base+1] := $FF;
  clrscr;
  Writeln('Battery charging / discharging measuring');
  Writeln('---------------------------------------');
  Writeln('Keys: ESC = Quit; 1 = reset time; 2 = switch mode; 3 = auto; 0 =
           turn off');
  mode := 0;
  assign(t,'data');
  rewrite(t);
  writeln(t,'sec@Volt@mA');

  b := 0;
  delta := 10; { 1 sample pr. 10 seconds }
{  delta := 1; { 1 sample pr. second }
  starttid := gettid;
  tid := starttid;
  autostart := starttid;
  a := 0;
  cmd := $FF;
  repeat
    gotoxy(1,5);
    Write('Mode: '); HighVideo;
    case Mode of
      0 : begin
            Write('Off');
            cmd := cmd or $30;
            port[base] := cmd;
          end;
      1 : begin
            Write('Charging');
            cmd := cmd or $30;
            cmd := cmd and not $10;
            port[base] := cmd;
          end;
      2 : begin
            Write('Discharging');
            cmd := cmd or $30;
            cmd := cmd and not $20;
            port[base] := cmd;
          end;
      3 : begin
            Write('Auto, ');
            if Auto = 1 then begin
              write('Charging');
```

```
          cmd := cmd or $30;
          cmd := cmd and not $10;
          port[base] := cmd;
        end
        else if Auto = 2 then begin
          write('Discharging');
          cmd := cmd or $30;
          cmd := cmd and not $20;
          port[base] := cmd;
        end
        else if (auto = 4) or (auto = 5) then begin
          write('Pausing for 5 min');
          cmd := cmd or $30;  { turn off }
          port[base] := cmd;
        end
        else begin
          write('Unknown/Error');
          cmd := cmd or $30;  { turn off }
          port[base] := cmd;
        end;
      end;
  end;
  clreol;
  writeln;
  NormVideo;

  { sample voltage: }
  gotoxy(1,8);
  Writeln('--- Sample Voltage: --------------------');
  for q := 1 to antal do begin
    gotoxy(1,9);
    { select A/D 2: }
{      cmd := $FB; 11111011}
    cmd := cmd and not 4;
    port[base] := cmd;
{      delay(1);
    { sample A/D 2: }
{      cmd := $F3; 11110011 }
    cmd := cmd and not 8;
    port[base] := cmd;
{      delay(1);
    { check if ready: }
    repeat
      a := port[base+5];
      a := port[base+1];
      gotoxy(1,wherey);
      write('sample ');
      if (a and 2) = 2 then
        write('not ');
      write('ready'); clreol;
    until (a and 2) = 0;
    writeln;

    { read data: }
    a := port[base+4];
    a := port[base];
    write('Data (port 340h) = ', a:3, ' = ',(a-7)/51:3:2,' V, status
           (port 341h) = ');
```

```
      buf1[b] := a;

      a := port[base+5];
      a := port[base+1];
      write(a and 3:3, ' (only 3 lsb)'); clreol; writeln;

      hi := 0;
      lo := 255;
      z := 0;
      r := 0;
      for c := 0 to antal do begin
        if (buf1[c] <> 255) and (buf1[c] <> 0) then begin
          if hi < buf1[c] then hi := buf1[c];
          if lo > buf1[c] then lo := buf1[c];
          z := z + buf1[c];
          inc(r);
        end;
      end;
      z := z div (r+1);
      z := z-7;  { calibrering så det passer med voltmeter }
      write('last ',antal,', high: ',hi:3,' = ',hi/51:3:2,'V, low: ',lo:3,
            ' = ',lo/51:3:2,'V, avg: ',z,' = ',z/51:3:2,'V');clreol;
      volt := z/51;
      clreol;

      { end sample: }
{      cmd := $FF;}
      cmd := cmd or 12;
      port[base] := cmd;
      { pause på min 600 ns: }
 {     delay(1); }
      b := (b + 1) mod (antal+1);
    end;

    gotoxy(1,13);
    Writeln('--- Sample Current: --------------------');
    { sample current: }
    for q := 1 to antal do begin
      gotoxy(1,14);
      { select A/D 1: }
{      cmd := $FE; 11111110}
      cmd := cmd and not 1;
      port[base] := cmd;
      shortdelay(500);
      { sample A/D 1: }
{      cmd := $FC; 11111100 }
      cmd := cmd and not 2;
      port[base] := cmd;
      shortdelay(500);
      { check if ready: }
      repeat
        a := port[base+5];
        a := port[base+1];
        gotoxy(1,wherey);
        write('sample ');
        if (a and 1) = 1 then
          write('not ');
        write('ready'); clreol;
```

```
    until (a and 1) = 0;
    writeln;

    { read data: }
    a := port[base+4];
    a := port[base];
    write('Data (port 340h) = ', a:3, ' = ',(a-10)/90:5:2,' V, status
           (port 341h) = ');
    buf2[b] := a;

    a := port[base+5];
    a := port[base+1];
    Sign := (a and 7) shr 2;
    write(a and 7:3, ' (only 3 lsb)'); clreol; writeln;

    hi := 0;
    lo := 255;
    z := 0;
    r := 0;
    for c := 0 to antal do begin
      if (buf2[c] <> 255) and (buf2[c] <> 0) then begin
        if hi < buf2[c] then hi := buf2[c];
        if lo > buf2[c] then lo := buf2[c];
        z := z + buf2[c];
        inc(r);
      end;
    end;
    z := z div (r+1);
    z := z-10;  { calibrering så det passer med voltmeter }
    write('last ',antal,', high: ',hi:3,' = ',hi/90:3:2,'V, low: ',lo:3,
          ' = ',lo/90:3:2,'V, avg: ',z,' = ',z/90:3:2,'V');

    amp := (z+4)*3.35;
    if Sign = 0 then amp := -amp;
    write('= ',amp:3:2,'mA');
    clreol;
    writeln;
    write('Sign = ', Sign, ' => ');
    if Sign = 1 then write('Charging')
    else write('discharging');

    { end sample: }
{      cmd := $FF;}
    cmd := cmd or 3;
    port[base] := cmd;
    { pause på min 600 ns: }
{      delay(1);}
    b := (b + 1) mod (antal+1);
  end;

  if mode = 3 then begin { determine what to do if auto }
    if auto = 0 then     { default to discharging }
      auto := 2;
    if (auto = 1) and ((tid-autostart >= 12000) or (amp < 50.0)) then
    begin
      autostart := tid;
      auto := 4;
    end
```

```
      else if (auto = 2) and (volt < 3.00) then begin
         autostart := tid;
         auto := 5;
      end
      else if (auto = 4) and (tid-autostart >= 300) then begin
         autostart := tid;
         auto := 2;
      end
      else if (auto = 5) and (tid-autostart >= 300) then begin
         autostart := tid;
         auto := 1;
      end
    end;

    gotoxy(1,21);
    Writeln('--- Sample Results: -------------------');
    Write('Time:    ', tid - starttid, ' s = ');
    write(lz((tid-starttid) div 3600),':',lz(((tid-starttid) div 60) mod
          60),':', lz((tid-starttid) mod 60));
    Write('; this delta: ', tid - autostart, ' s = ');
    writeln(lz((tid-autostart) div 3600),':',lz(((tid-autostart) div 60)
            mod 60),':',lz((tid-autostart) mod 60),'        ');
    Writeln('Voltage: ', volt:3:2, ' V   ');
    Writeln('Current: ', amp:3:2, ' mA   ');
    Write('State:   ', mode,',',auto, ' (3=auto; 2=disharge; 1=charge;
           0=off)');

    { write output file: }
{    writeln(t,'sec@Volt@mAmp@state');}
    writeln(t,tid-starttid,'@',volt:3:2,'@',amp:3:2,'@',mode,'@',auto);

    { beregn -\|/- }
    snr := ((snr+1) mod 4);

    { wait for next sample: }
    gotoxy(52,25);
    repeat
      gotoxy(52,wherey);
      write('Next sample in: ',tid+delta-gettid,' seconds  ');
      { write -\|/- }
      gotoxy(79,25);
      write(str[snr+1]);
    until (tid+delta <= gettid) or keypressed;
    gotoxy(1,whereY-1);
    tid := gettid;

    if keypressed then begin
      key := readkey;
      if key = #0 then key := readkey;
      if key = '0' then begin mode := 0; end;
      if key = '1' then begin
        Starttid := gettid;
        autostart := tid;
      end;
      if key = '2' then begin
        if mode = 3 then mode := 0
        else mode := (mode+1) mod 3;
        if (mode = 1) or (mode = 2) then
```

```
          autostart := tid;
      end;
      if key = '3' then if (mode = 1) or (mode = 2) then begin
                          auto := mode;
                          mode := 3;
                        end;
    end;
  until key = #27;
  close(t);
  while keypressed do
    key := readkey;
  port[base] := $FF;   { => no A/D's selected }
  port[base+1] := $FF;
end.
```

Appendix E - Measuring of I/V and P/V Curves for Solar Cells

2 pages

Appendix E - I/V and P/V Curves for Solar Cells

Early in the project we wanted to create an array of solar cells in order to be able to charge a battery from solar energy. The first cells we got were only available as 5 pieces, but we were promised that we could get some additional cells within a couple of weeks. This turned out not to be true, so in the end we purchased some other cells.

The reason that we created the I/V characteristic of the original cells was that we didn't know the manufacturer, and therefore couldn't get the data, although they were originally sold as 0,5V, 200 mA this turned out not to be true. We expect that the numbers given are open circuit voltage and short circuit current.

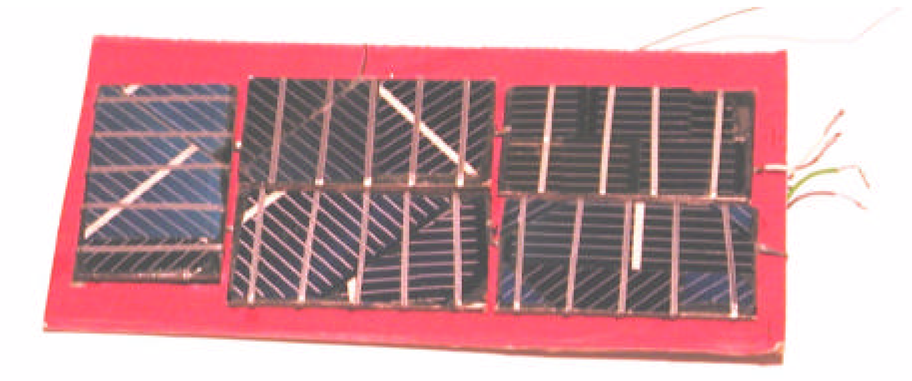


Figure E-1 - The solar cells we tested

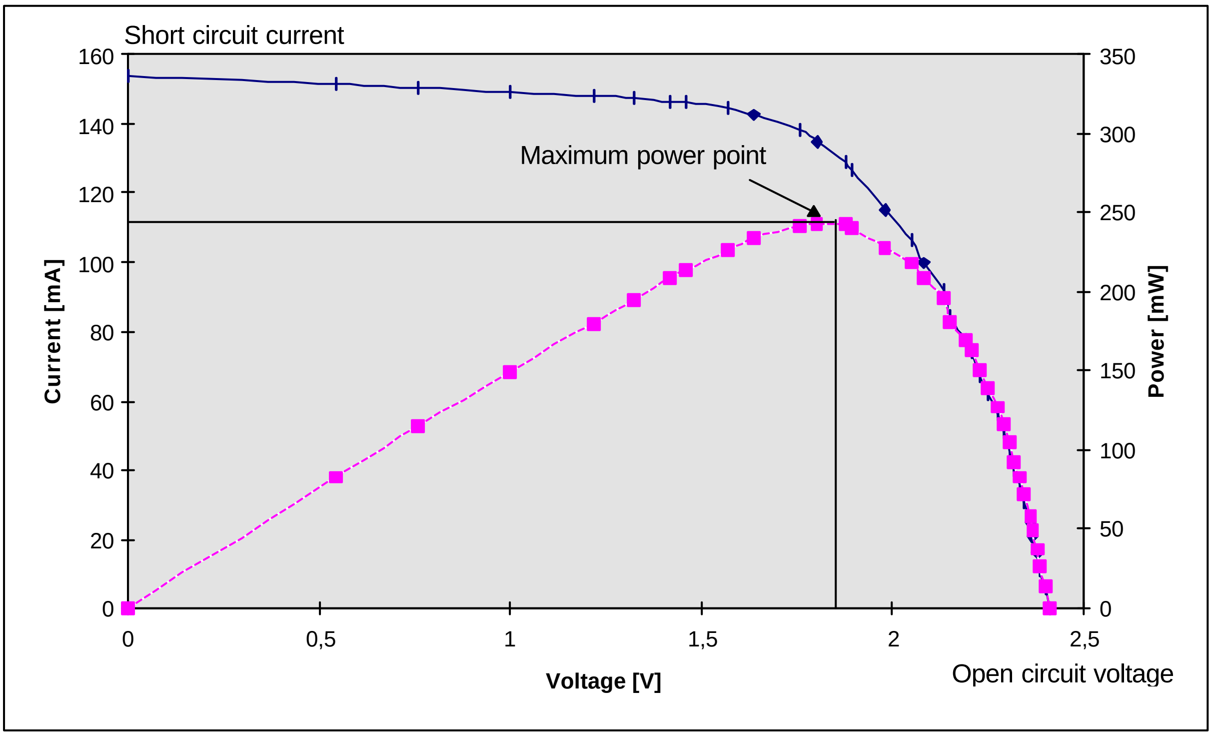
The test was performed by measuring the voltage across 5 cells connected in series. A variable resistor was used as a load. The current through the resistor was also measured, and the data set was used to calculate the power: $P = U \cdot I$.

```
Date:          9.11.2001,
Temperature:   The temperature was held constant at 52 °C.
Illumination:  The illumination was provided by a 75W glow lamp,
               the bulb was located 10 cm above the cells.
```

U (V)	I (mA)	P (mW)
0	153,7	0
0,5423	151,4	82
0,76	150,2	114
0,9965	149,5	148
1,215	148,2	180
1,322	147,6	195
1,418	146,7	208
1,459	146,4	213
1,566	144,7	226
1,642	142,6	234
1,757	137,8	242
1,804	134,4	242
1,881	128,8	242
1,895	126,5	239
1,979	115	227
2,05	106,4	218
2,083	99,8	207
2,131	91,8	195

U (V)	I (mA)	P (mW)
2,15	84,4	181
2,193	77	168
2,208	73,6	162
2,232	67,2	149
2,253	61,9	139
2,275	55,6	126
2,293	50,6	116
2,308	45,3	104
2,319	40,1	92
2,331	35,3	82
2,344	30,6	71
2,36	24,7	58
2,37	20,8	49
2,382	15,6	37
2,39	10,9	26
2,401	5,6	13
2,415	0	0

The above numbers result in the following I/V and P/V graph:



It is evident that I_{SC} is less than the specified 200 mA, a more correct value would be 150 mA, also we can estimate $U_{OC} = \frac{2{,}4V}{5} = 0{,}48V$, which is pretty much the specified value.

Of, course you would expect the vendor of the cells to specify the maximum power point voltage and current, since these values are telling more about how the cells operate in a real circuit. These values can be measured to: I_{MP} = 135 mA, and $U_{MP} = \frac{1{,}85V}{5} = 0{,}37V$. Also the maximum power can be calculated as $P_{MP} = U_{MP} \cdot I_{MP} = 135mA \cdot 1{,}85V = 250$ mW.

Appendix F - Power Calculations

2 pages

Power Demands:

		Requested Voltages	Max deviation	Max current, DC	Max ripple	ripple freq	dutycycle		Power (as reported by the group)
Attitude	**Magnetorquers**	3 - 4 V	unstabilised	<= 50 mA	10 mApp	1 kHz	990 ms/s	detumble	50 mW < x < 150 mW
		"	"	"	"	"	"	stabilizing	<= 50 mW
	Magnetometer 1	>= 3,2 V	stabilised (± ?V)	<= 20 mA	uspec	uspec	10 ms/s		<= 1mW(avg)
	Magnetometer 2	"	"	500 mA	uspec	uspec	12 - 30us/s		not reported
	Sunsensor	3 - 4V	unstabilised	4 mA	uspec	uspec	20 ms/s		<=0,5mW(avg) 15mW for 20 ms
OBC	**Normal operation**	3,3 V el 3,0 V	± 0,3 V	50 mA	uspec	uspec	100%		not reported
	Bootup	"	"	110 mA	uspec	uspec	1 s / boot		not reported
	Upload	"	"	110 mA	uspec	uspec	? s / upload		not reported
Radio	**Beacon**	2,7 - 3,3 V	± 0,3 V	2 mA	uspec	uspec	100%		not reported
	Receiver	"	"	20 mA	uspec	uspec	100%		not reported
	Transmitter	"	"	20 mA	uspec	uspec	4 x 15 min / 12 hour		not reported
	PA	3 - 5 V	"	uspec	uspec	uspec	4 x 15 min / 12 hour		1 W i 15 min / 3 hour
Camera		3,3 V	uspec	25 mA	uspec	uspec	5 min pr 90 min		not reported
Thether		3,3 V	uspec	5 mA	uspec	uspec	100%		not reported

Appendix F - Power calculations

battery capacity:	5550	mWh	2590	=700*3,7
solar cell power:	1000	W	5550	=1500*3,7
power demand, normal:	410	mW/s		
power demand, transmitting:	1476	mW/s		

	Duration min	Time min	0=low 1=transm.	Illuminated 0=no 1=yes	Power Demand mW/s	Power Input mW/s	Energy Usage mWh	Energy Available mWh	Energy Balance mWh	Energy Surplus mWh	Battery State mWh	DOD %
Transmitting when dark:	0	0								0	5550	0,00
Dark:	20	20	0	0	410	0	137	0	-137	-137	5413	2,46
Dark, transmitting:	15	35	1	0	1476	0	369	0	-369	-506	5044	9,11
Lit:	63	98	0	1	410	1000	431	1050	620	114	5550	0,00
Transmitting when lit:	0	0								0	5550	0,00
Dark:	35	35	0	0	410	0	239	0	-239	-239	5311	4,31
Lit, transmitting:	15	50	1	1	1476	1000	369	250	-119	-358	5192	6,45
Lit:	48	98	0	1	410	1000	328	800	472	114	5550	0,00
Not transmitting:	0	0								0	5550	0,00
Dark:	35	35	0	0	410	0	239	0	-239	-239	5311	4,31
Lit:	63	98	0	1	410	1000	431	1050	620	380	5550	0,00

Appendix G - Vacuum Test of Batteries

1 page

Appendix G - Vacuum Test of Batteries

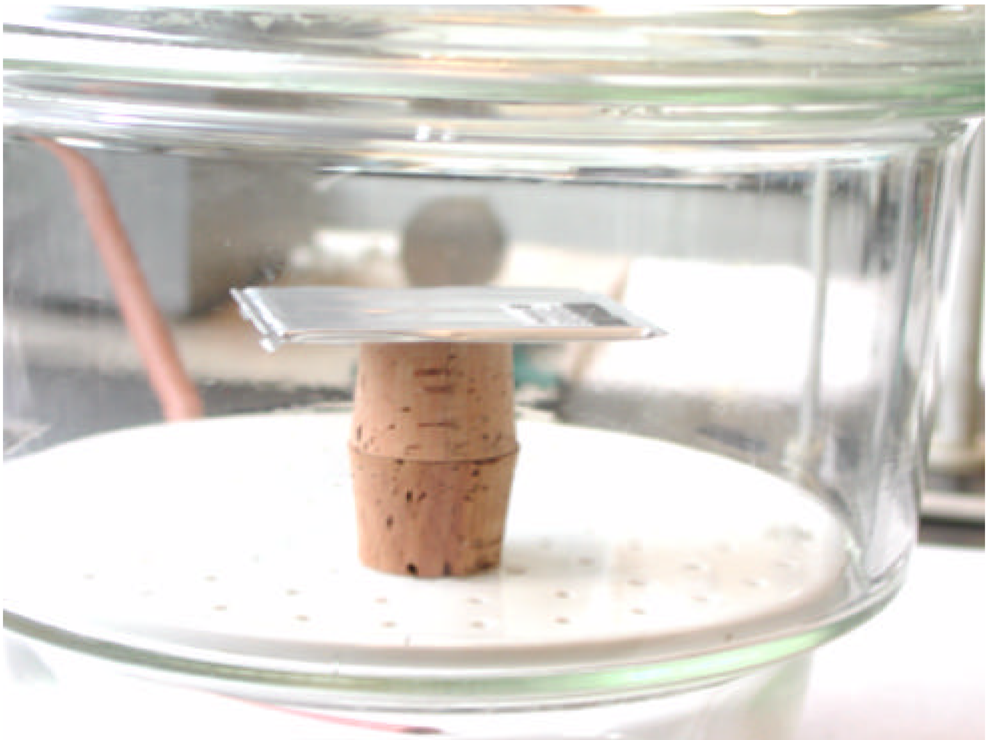


Figure G.1 - Before the test

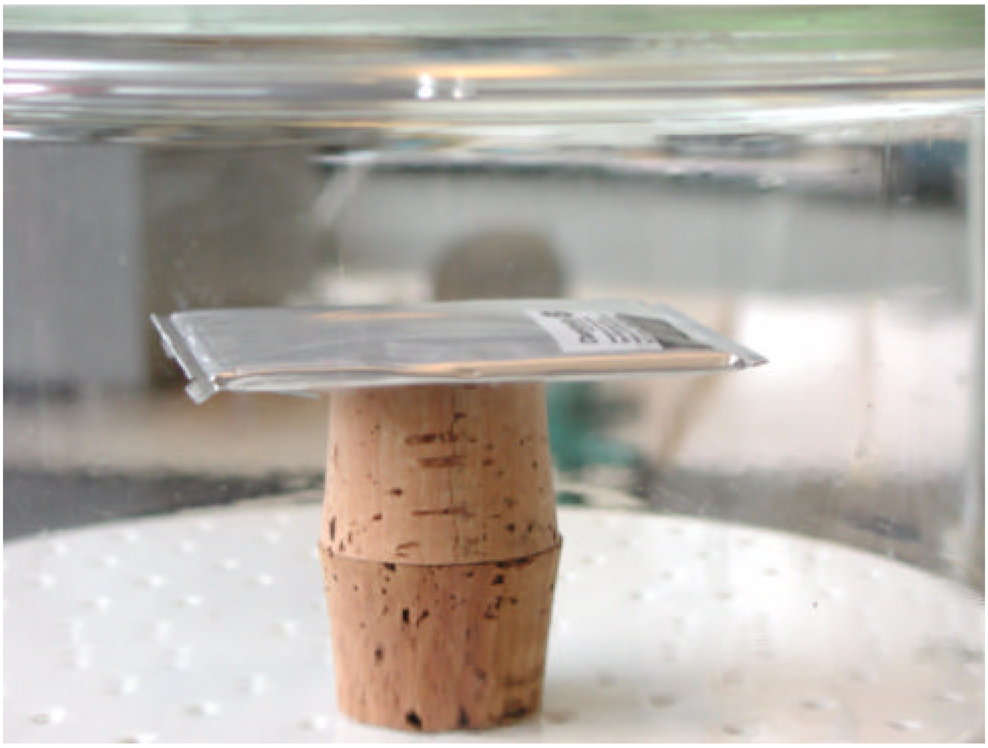


Figure G.2 - The battery swelled up during the test at 10^{-5} Torr

Appendix H - Radiation Test of Max890

1 page

Appendix H - Radiation test of Max890

VIn=+3V, TA=0 to 85C, unless otherwise noted, typical @ 25C

		Datasheet			Radiation Test				
	Conditions	Min	Typ	Max	0 Rad	1 kRad	2 kRad	5 kRad	
Operating Voltage		2,7		5,5	min 2,3			min 2,3	V
Quiescent Current	VIn=5V, /ON=GND, IOut=0		13	20	13			13,5	uA
Off-Supply Current	/ON=IN, VIn=VOut=5,5V		0,03	1	-			-	uA
Off-Switch Current	/ON=IN, VIn=5,5V, VOut=0		0,04	15	0,5			0,5	uA
Undervoltage Lockout	Rising edge, 1% hysteresis	2	2,4	2,6	-			-	V
On-Resistance	VIn=3,0V		90	150	110			120	mOhm
Current-Limit-Amplifier Threshold	VSet required to turn the switch off	1,178	1,24	1,302	1,252			1,240	V
Maximum Output Current Limit			1,2		-			-	A
IOut to ISet Current Ratio	IOut=500mA, VOut > 1,6V	970	1110	1300	***			***	A/A
/ON Input Low Voltage	VIn=2,7V to 5,5V			0,8	1,30			1,15	V
/ON Input High Voltage	VIn=2,7V to 3,6V	2			1,49			1,22	V
/ON Input Leakage Current	V/On = 5,5V		0,01	1	-			-	uA
ISet Bias Current	VSet=1,24V, IOut=0, VIn=VOut		0,5	3	-			-	uA
/FAULT Logic Output Low Voltage	ISink=1mA, VSet=1,4V			0,4	-			-	V
/FAULT Logic Output High Leakage Current	V/FAULT=5,5V, VSet=1V		0,05	1	-			-	uA
Slow-Current-Loop Response Time	20% current overdrive, VCC=5V		5		-			-	us
Fast-Current-Loop Response Time			2		-			-	us
Turn-On Time	VIn=5V, IOut=500mA		120	200	-			-	us
	VIn=3V, IOut=500mA		185		-			-	us
Turn-Off Time	VIn=5V	2	5		-			-	us

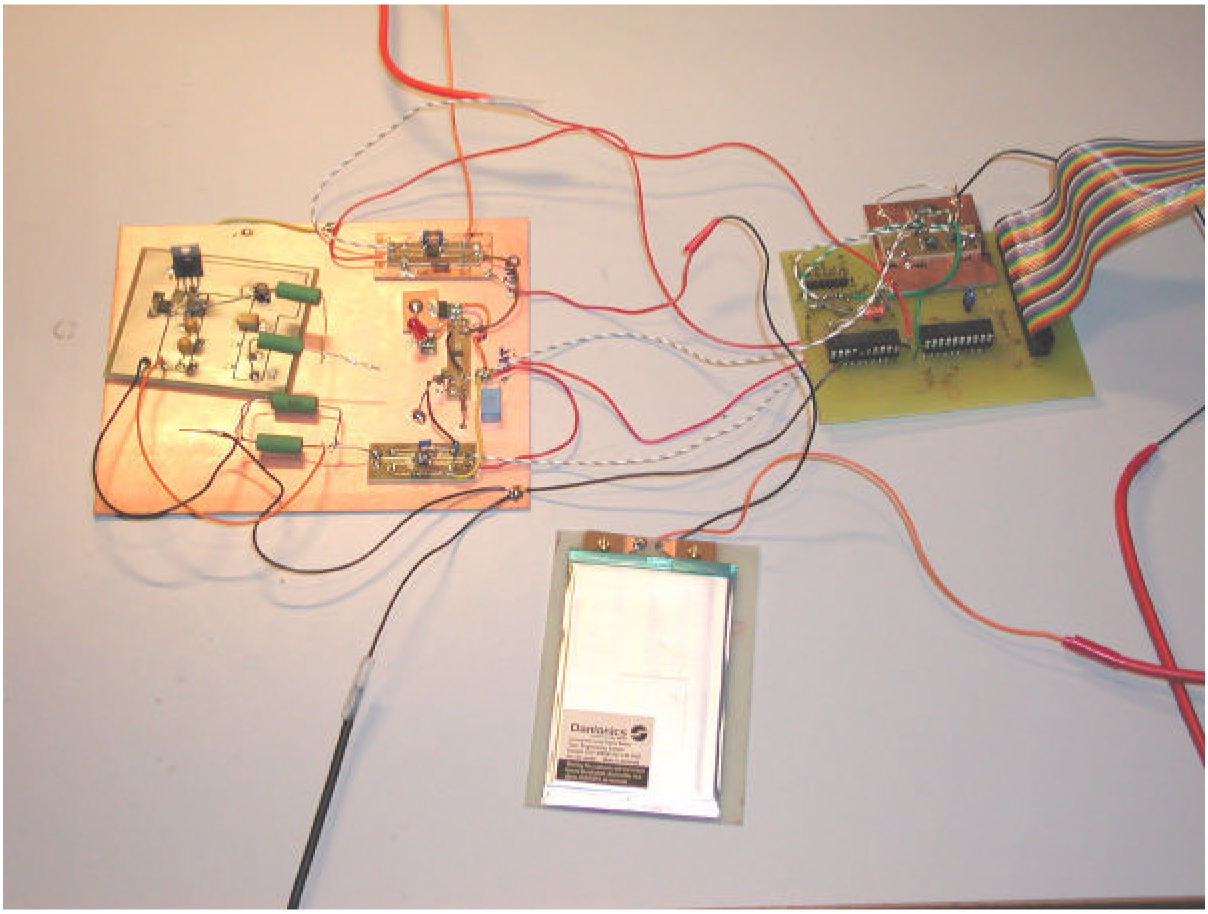
*** was tested like this:

	0 Rad	5 kRad	
ISet=	98,2	96,9	uA
IOut=	182,4	175,8	mA
IOut/ISet=	1857,434	1814,241	A/A

Appendix I - Picture of the Power Supply

1 page

Appendix I - Picture of the Power Supply



Appendix J - Datasheet for Spectrolab Solar Cells

2 pages

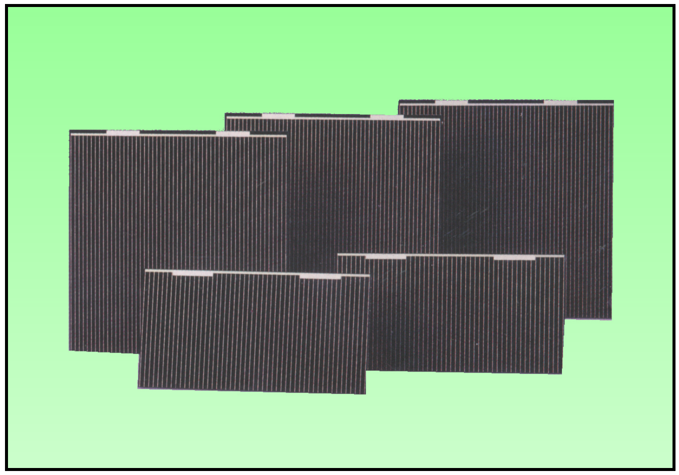
S P E C T R O DATA

$GaInP_2/GaAs/Ge$ Dual Junction Solar Cells

Features

- High efficiency n/p design
  - -Integral bypass diode protection
  - -Transparent insertion into existing systems

- High volume production capability:
  - -Currently delivering 21.5% minimum average efficiency solar cells



Product Description

Substrate	Germanium
Method of GaAs Growth	Metal Organic Vapor Phase Epitaxy
Device Design	Monolithic, two terminal dual junction. n/p $GaInP_2$ and GaAs solar cells interconnected with a tunnel junction
Sizes	Up To 30 cm^2
Assembly Method	Multiple techniques including soldering, welding, thermocompression, or ultrasonic wire bonding
Integral Diode	Si diode integrated into recess on back side
Note: Other Variations Are Available Upon Request	

Heritage

- More than 600 kW of multi-junction cells produced
- More than 100 kW of multi-junction arrays ***on orbit***
- 1 MW annual capacity - cells, panels & arrays
- On orbit performance for multi-junction solar cells validated to ± 1.5% of ground test results

S P E C T R O L A B

A **BOEING** COMPANY

Spectrolab, Inc.
12500 Gladstone Avenue
Sylmar, California, USA 91342-5373
Ph: 1 (818) 365-4611 Fax: 1 (818) 361-5102

GaInP$_2$/GaAs/Ge Dual Junction Solar Cells

S P E C T R O **D A T A**

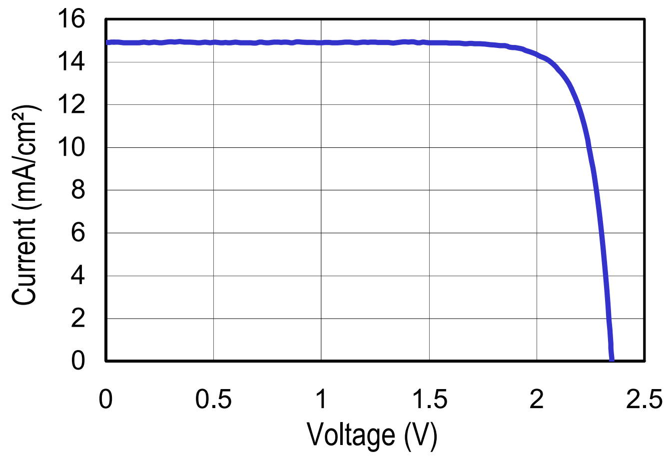
Typical Electrical Parameters

(AMO (135.3 mW/cm²) 28°C, Bare Cell)

J_{sc}= 15.05 mA/cm²
J_{mp}= 14.15 mA/cm²
$J_{load\ min\ avg}$= 14.20 mA/cm²
V_{oc}= 2.360 V
V_{mp}= 2.085 V
V_{load}= 2.050 V
Cff= 0.83
Eff_{load}= 21.5%
Eff_{mp}= 21.8%

Typical IV Characteristic

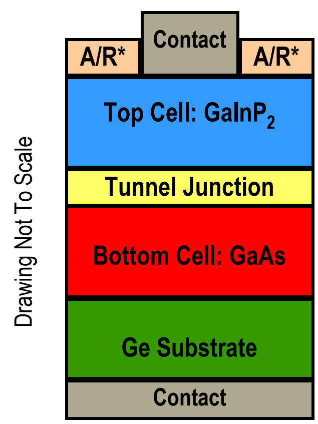
AMO (135.3 mW/cm²) 28°C, Bare Cell



Radiation Degradation

(Fluence 1MeV Electrons/cm^2)

Parameters	$1x10^{14}$	$5x10^{14}$	$1x10^{15}$
Imp/Imp_0	1.00	0.96	0.92
Vmp/Vmp_0	0.96	0.93	0.91
Pmp/Pmp_0	0.96	0.89	0.83



*A/R: Anti-Reflective Coating

Thermal Properties

Solar Absorptance= 0.92 (Ceria Doped Microsheet)
Emittance (Normal)= 0.85 (Ceria Doped Microsheet)

Weight

84 mg/ cm² (Bare) @ 140 µm (5.5 mil) Thickness
Thickness of 175 µm typical with weight equivalence of a 140 µm thick cell.

Temperature Coefficients

Parameters	BOL	$1x10^{15}$ (1 MeV e/cm²)
Jmp (µA/cm²/°C)	8	13
Jsc (µA/cm²/°C)	10	12
Vmp (mV/°C)	-4.6	-5.0
Voc (mV/°C)	-4.2	-4.8

S P E C T R O L A B

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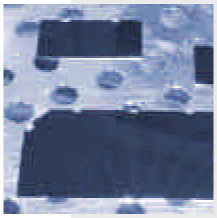
Appendix K - Datasheet for Emcore Solar Cells

2 pages

InGaP/GaAs/Ge Triple-Junction Solar Cells



Solar Cell Characteristics

- True Triple-Junction n on p polarity
- Epitaxial materials grown in EMCORE *Turbo*Disc® MOCVD reactors with proven excellent uniformity and repeatability
- Cells can be welded or soldered
- Size: 76.10 ±0.05 x 37.16±0.05 mm^2 with two cropped triangular corners of 8.5 x 8.5 mm^2, or any custom sizes
- Area: 27.5 cm^2 standard or up to 30 cm^2
- Thickness: 155 µm (6 mil), uniform thickness
- Mass: 2.4 g (including one by-pass diode), 86 mg/cm^2

Features and Benefits

- Triple-junction 26.0% BOL efficiency
- Highest radiation resistance: P/Po =0.91 @ 1-MeV, 5E14 e/cm^2
- Advanced product roadmap for higher efficiencies
- Mechanical strength enhanced 3X for reduced attrition in CIC and laydown
- Smooth rear surface for ease of laydown with reduced adhesive
- ISO 9001 certified

Basic Triple-Junction Structure

InGaP Junction
GaAs Junction
Ge Junction
Ge Substrate

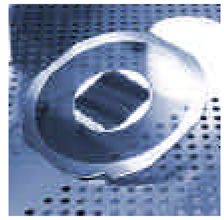
Typical Performance Data

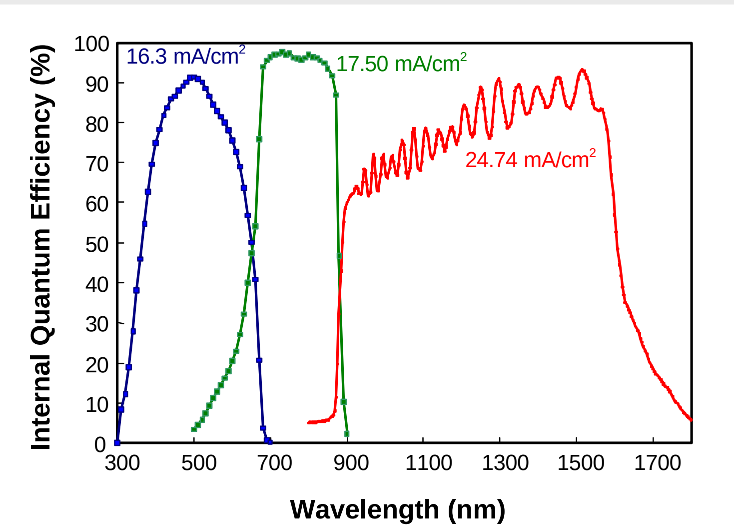
BOL Efficiency at 28° C:	26.0%
Remaining Power after 1E15 e^-/cm^2:	0.87
Remaining Power after 5E14 e^-/cm^2 :	0.91
Temperature Ceofficient :	0.060 abs.%/°C
EOL Efficiency at 5E14 e^-/cm^2 :	23.7%

InGaP/GaAs/Ge Triple-Junction Solar Cells

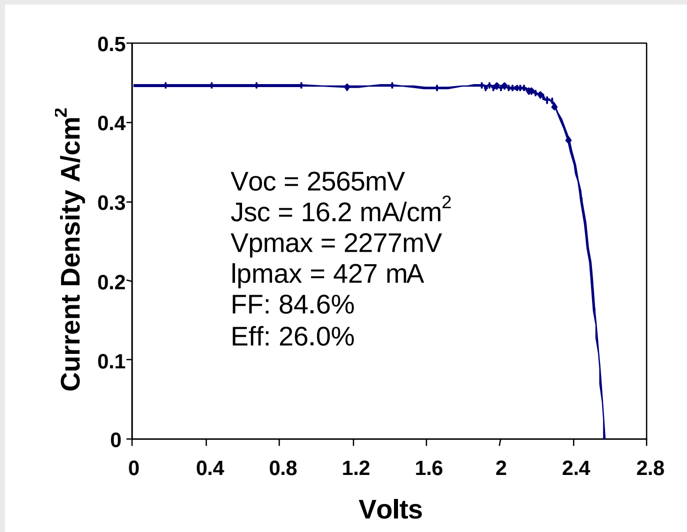
Space Qualification Results

Test	Description	Results
Humidity	+45°C, 95% RH, 30 days	<0.16%
Thermal	2000 Cycles, -180 to +95°C	<0.2% Degradation
Radiation	1 MeV: 1E15 e/cm^2 Electrons: 5E14 e/cm^2	$P_{mp} / P_{mpo} = 0.87$ $P_{mp} / P_{mpo} = 0.91$
Absorbance	CMG MgF_2 coated	0.90

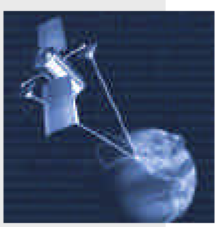




Beginning-of-Life current generation in the multi-junction stack designed for best End-of-Life performance



Flight cell Beginning-of-Life efficiency for any shipment to range from 24.5% to 28%



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EMCORE

Appendix L - Datasheet for Danionics Battery

1 page

LITHIUM-ION POLYMER BATTERIES · DLP 305590

HANDHELD BATTERY

- A 1000 mAh battery for PDA, handheld device & smart phone applications

Specifications

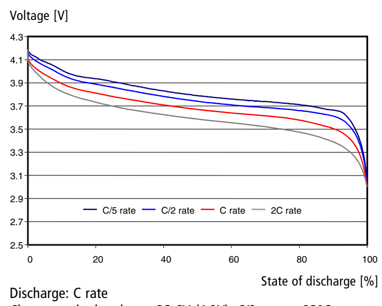
Name:	DLP 305590
Weight:	31 g
Capacity (C/5):	1000 mAh
Nominal voltage:	3.7 V
Voltage range:	3.0 – 4.2 V

Features

The Danionics Lithium-Ion Polymer Technology offers a high degree of design freedom. The DLP 305590 battery from Danionics features:

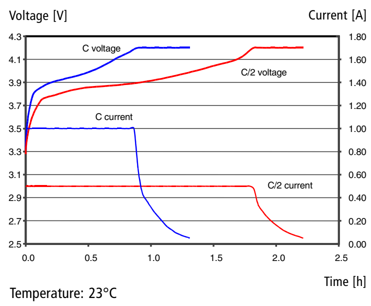
- High energy density
- High voltage
- High current charging characteristics
- Long cycle life
- Low self discharge
- Attractive flat prismatic form factor
- Good temperature and storage performance

Discharge characteristics



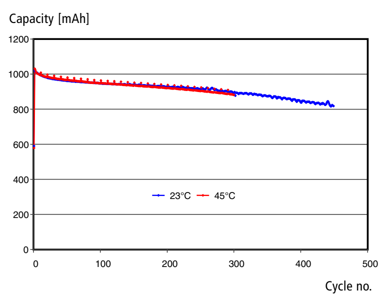
Discharge: C rate
Charge method and rate CC-CV (4.2V): C/2 rate at 23°C

Charge characteristics



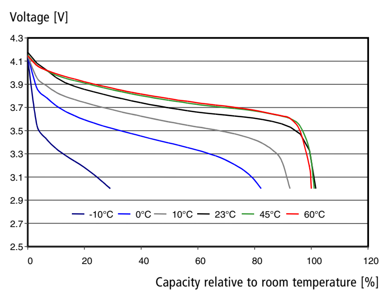
Temperature: 23°C

Cycling characteristics



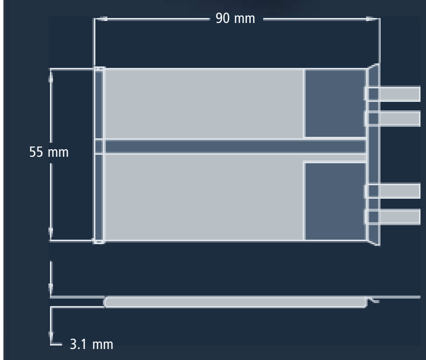
Discharge: C rate
Charge method and rate: CC-CV (4.2V): C/2 rate

Temperature characteristics



Discharge: C rate
Charge method and rate CC-CV (4.2V): C/2 rate at 23°C

The Danionics Lithium-Ion Polymer Battery offers through a combination of high energy and power density, a polymer electrolyte and soft packaging concept distinct advantages to Original Equipment Manufacturers in the portable electronics industry.



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Danionics POWER ON THE MOVE™