Abstract

This report has been written as a part of the DTUsat project covering the radio hardware. It covers the selection of the different chipset for the satellite transceiver and the prototype design process. An overview of the peripheral electronic needed is established. The possibilities for frequency allocation are discussed, and a frequency application is presented.

The effect of the ionizing radiation in space on the components is presented and different radiation test are discussed. A link budget for the complete physical radio link is presented and the results are discussed. The interface between the radio hardware and the other groups in the satellite is documented. A possible ground station solution is presented and analyzed.

Problem Description

In the spring of 2001, a group of students at the Technical University of Denmark got the idea of a student satellite. Two weeks before the fall semester 2001 started, a special course was arranged, giving the participants an overview of the problems of satellite construction. A number of groups were formed among the participants to design and build the different modules for the satellite. We chose to work on the radio transceiver, as it needed doing and sounded quite exciting, but none of us have prior experience with radio hardware.

We started a special course at the section of Electromagnetic Systems at Ørsted-DTU. The course ran from September 2001 to January 2002 inclusive and covered 7.5 ECTS-points. This report is the result of that special course, and was delivered on the 25th of February 2002. The purpose is:

To design and build a space qualified radio transceiver for the student satellite at the Technical University of Denmark, DTUsat.

The project focus has spread out as we progressed, as it turned out that the satellite was in need of an entire communications system design before anyone could begin designing and building specific radio transceiver modules. As no one else lifted this task, we had to do it ourselves. This has changed the project from a relatively straightforward design problem to a total system analysis and requirement specification problem. We have tried to maintain some focus on building the physical transceiver, but as no one started out with a final plan for the finished satellite, we have had to write the requirement specifications in cooperation with the other groups working on the satellite as we progressed. This has made the entire DTUsat project extremely exciting and very time consuming. This project has grown in all directions at once, as we have tried to cover every aspect of the communication link, from choosing and getting permission to use the frequencies on which we will operate to sketching a ground station proposal. In between, we have worked on the original problem and taken up the problem of radiation damage to electronic components in space. In the end, we ended up testing components for all hardware groups.

We would like to extend our thanks to the following people for help during the project.

Flemming Hansen, Technology Manager at Danish Space Research Institute (DSRI)
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- Nordic VLSI
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- Sprague-Goodman electronics and their Danish distributor, Fredslund
- Maxim Semiconductors

- CoilCraft
- RF Microdevices

General remarks: References to other DTUsat groups are not always written out in full. They and their reports can be found on the DTUsat homepage at http://www.dtusat.dtu.dk. References to files are found in Communication/Radio Hardware/Files on the home page under the directory Report. It is fully accessible, also without logging in.

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General description of DTUsat

DTUsat is a very small satellite, which a group of around 40 students are currently designing and building at the Technical University of Denmark. Once completed, it will measure 10x10x10 cm and weigh 1 kg. The small dimensions will ease the launch remarkably. This is primary due to the mechanical dimensions that are standardized so the satellite can be launched together with other so-called Cubesats on a common launch tube. Thereby one avoid having to find a rocket with spare payload for a small satellite and inventing some way mounting it on to the rocket during launch. The Cubesat-concept originates from Stanford University[1] and has rapidly become very popular since it shortens developing time and -expenses for hobby satellites drastically.

The project started as an idea in the spring of 2001 and really took off with a course held in the last two weeks of the summer vacation. We are counting on launching the DTUsat in the spring of 2003. So far, it is not known what orbit it will be launched to, but it will probably be a polar orbit with an altitude of 650 km. This means that the satellite will pass the entire earth twice a day.

The total budget is 1.4 mio dkr, which corresponds to about $160.000 including launch. That is a very cheap satellite indeed! We have funded one third so far but still need to finance the launch. We believe that the launch and operation will attract a lot of public attention. Our sponsors will be placed on our website that will display data received from the satellite.

Purpose

Since DTUsat is a university project the main purpose is to educate engineers. This project gives students the opportunity to work together in a large group, far bigger then any other found on DTU, experiencing the problems and benefits this generates. The satellite project currently occupies 38 students, but hopefully, this rises to 60 in the spring semester of 2002. This means that a surprising amount of time is spent on communication, planning interfaces for the modules, and corporation between groups and courses.

Apart from educating engineers, we see a great PR-potential in DTUsat. We think that DTUsat presents a possibility to eliminate some of the prejudices that exist on being a engineer and thereby attract new students to the education, if it can be communicated to the public how creative and enjoyable the work on it is. We have plans on doing the ground station public available via the Internet so e.g. high school students can download data from the satellite.

Project Success Criteria

To be able to evaluate the DTUsat project, we have set some prioritised success criteria.

1. Everybody should learn something. This goal has already been fulfilled but the potential has not yet been exhausted.

[1] Original idea by professor Robert Twiggs at Stanford Space Systems Development Laboratory, http://ssdl.stanford.edu/cubesat/

2. To complete and document the different modules so that other projects might benefit from them and there is no need to start from scratch if a group or individual abandons the project before it is finished.
3. To receive data from the satellite telling us the status on the different modules.
4. To establish two-way communication with the satellite.
5. To gain full control of the satellites orientation in space.
6. To receive pictures of the earth and/or the separation from the rocket.
7. To change the satellite orbit using the electro dynamic tether.

The priority has been carefully laid down. It is decided by a combination of 1) the number of subsystems that need to operate before a success criterion is fulfilled and 2) the mission risks involved in reaching the single objectives.

Project Organisation

There is a lot of work in designing and building such a small satellite. To handle this we have organised us in 11 groups each working with one of the subsystems the satellite consist of. Each group, consisting of 1-6 individuals, has a supervisor from DTU appointed to make sure that work progresses and that the group does not get stuck anywhere.
The strings are gathered in a group called the System Engineering group. Its purpose is to make sure that the groups work together toward a common satellite that can be operational. The System engineering group also keep track of interfaces between the subsystems, makes sure that power, weight and economical budgets are fulfilled and sees to it that no single part of the satellite is forgotten e.g. if all the groups thought that another group were handling this part. Besides it operates as an idea forum – if a group are stuck with a problem, often another group has inspiration to offer. The System Engineering group is an open forum, but almost every subsystem groups have appointed a regular representative.
Besides these groups there exists a guidance group and a supervisor group. The guidance group includes members from Danish space companies and institutions, and representatives from the students and supervisors. The Guidance group also has the overall responsibility for financial part of the project. The supervisor group is more informal and consists of the supervisors who are attached to the project. Both groups have the objective to keep an eye on the project and try to catch any slip-ups that might occur in System Engineering.

Technical Purpose of DTUsat

One of the satellite payloads is an electro-dynamic tether, a 1 km long aluminium string picking up the free electrons that exists in space. By emitting the picked up electrons from the satellite, a current will flow in the string. Because the satellite is in motion in the magnetic field of the earth, it will result in a force on the satellite, making it possible to change the orbit without the use of fuel. Variants of this experiment have failed for both NASA and ESA. Maybe we will succeed?
The second payload is three-axis attitude control system that can make the satellite turn to face any direction in space. By using electromagnets we can make the satellite adjust itself according to the earths magnetic field in the same way as a compass needle. However, some inherent problems make it hard to obtain a good control over the satellite using this technique. The magnetic field lines change according to the satellite position, and it is impossible to rotate the satellite around the field lines. This makes it a low-key attitude

control system, but the advantages are no need for heavy, power-hungry mechanics or fuel. Only coils, current, computational power and time are needed to control the attitude. The attitude control system is not normally included as a payload, but rather as a part of the satellite platform.

The third payload consists of a camera that can take images of the earth mostly for PR purposes. We do not expect to produce high-quality pictures, but it could be fun if we could recognize Denmark and see how the weather is in Timbuktu on an image from our very own satellite. Besides it is a payload that is easily understood and presented to laypersons.

The fourth payload is a test transmitter that can help radio amateurs testing the sensitivity of their equipment. This transmitter is a returned favour to the international amateur satellite association, AMSAT, for letting us use one of their frequencies to communicate with the satellite. In return they want some radio amateur use for the satellite, which is hard to do because of the limited power we have available. Our idea is to transmit a message a number of times but with less and less power. The signal strength of the last message that the radio amateur receives gives him an indication on how sensitive his rig is.

Requirements Specification

The primary design goal is a bi-directional connection between earth and our satellite. It must be possible to transmit commands and receive data – if not, the satellite could just as well not exist. The configuration of the satellite places certain requirements and constraints on the radio transceiver[2].

1. The small size and consequently small power budget of the satellite demands a small radio with low power requirements. It also limits the antenna possibilities to alternatives, which can fit in the envelope.
2. The payloads, especially the camera, will require a certain downlink bandwidth to be useful. Also, we would like to be able to log e.g. temperature data for an entire orbit, which also consumes bandwidth.
3. The software group would like to be able to upload new software modules to the computer. This means places demands on the uplink bandwidth.
4. The satellite environment is very hostile. The radio needs to be capable of functioning under these circumstances.
5. The experimental nature of all subsystems requires the radio to be tolerant of disturbances, both electronic and mechanical. E.g., we can not be sure that the attitude control system works perfectly all the time, or that the processor will not emit radio noise.
6. To be able to integrate all components to a satellite, the radio connections must be compatible with other groups.

The size and weight budget are set to approximately 6 by 6 centimeters of board area and roughly 40 grams maximum. The satellite is, of the latest mass budget revision, about 80 grams overweight, so every gram counts.

The power budget is very limited. The small surface area of the satellite limits the room for solar cells, and less than 3 W is available at the best. Considering converter loss, battery loss and that energy must be stored for the dark periods of the orbit, 1 W is a reasonable sustained power. However, peak power might be higher, and as we are transmitting for relatively short periods of time, our power requirements are not as strict as the systems that are always on.

The downlink bandwidth is determined from how much data we need to transmit. The satellite orbit is expected to be polar with an inclination of 80-100 degrees, an altitude of about 600 km, and a period of 100 minutes, which will give us a communication window of up to 12 minutes per orbit. We expect to have radio view of the satellite for about 2-3 successive periods of varying duration, followed by about 4-5 orbits of radio eclipse. Further details are not known at this time. For the raw telemetry[3], we expect to log maximum 50 bytes every 10 seconds. This translates to a data generation of 30 kb/orbit. An eclipse of 5 orbits will have 150 kb of data waiting in the satellite. We would like to get this amount of data down in half a maximum communications window, that is, 6 minutes. The net data rate should be at least 3413 bps to be able to do this. As we expect a

[2] All these constraints are controlled by the System Engineering group.
[3] Data coming down from the satellite

significant overhead, the downlink rate should be considerably larger than this. The camera payload further increases the bandwidth requirements. Even if the pictures are compressed on board the satellite, it will still require some time to download them. However, when the camera is commissioned, we probably do not need the very detailed logging, but only status messages. This can transfer bandwidth from the logs to pictures, not increasing the total. Also, we expect more passes in a row, so a downlink bandwidth requirement of at least 4800 bps is satisfactory. In practice, 9600 bps is more standardized.

The uplink bandwidth is determined by the need to upload new software to the radio. If this is possible, the radio should be able to receive a block of at least 32 kb in one 12 minute pass. This translates to a net bandwidth requirement of 364 bits per second. Allowing for overhead, a raw bandwidth of at least 1200 bits per second will be necessary. However, we plan to provide the same bandwidth for the uplink as for the downlink.

We have chosen to use half-duplex communication, as the data stream will primarily be unidirectional, and as full-duplex requires more resources of any kind – two frequency allocations, two sets of antennas, etc.

The environment demands must be fulfilled unconditionally. No matter how harsh the environment, the satellite must be able to endure it. If possible, the radio should also not be disturbed even by very noisy nearby electronics. However, we have some influence on this.

The mechanical and electrical compatibility issues are resolved in the System Engineering group.

Frequency Allocation

There are many factors to consider when choosing a frequency for a satellite. As the satellite footprint covers every single country in the world, getting a frequency assigned is not very easy. The frequency determines not only the size and possible construction methods of the antennas, but also the transmission loss and the circuit design complexity.

As the satellite will pass every single local communications agency worldwide, getting a global frequency assigned would be a nightmare. Actually, there is only one global organization that has real control over frequency bands, and that is the amateur radio or ham society. The radio amateurs have had control of some frequency bands almost since the birth of radio communication and have managed to keep them reserved for use by amateurs. The radio amateurs passed into the space age in 1961, only 4 years after it started, by putting a small beacon satellite into orbit. In 1969, an organization for amateur satellite radio was started, and it was assigned a part of some of the frequency bands[4]. However, AMSAT would probably not have kept control if they assigned frequencies to anyone who asked. In order to use their frequencies, the satellite must have an amateur radio purpose. According to the rules of the International Radio Amateur Union (IARU), this is, quote[5]

[4] http://www.amsat.org/amsat/sats/n7hpr/history.html
[5] http://www.iaru.org/satellite/prospective.html

A. To provide communication resources for the general amateur radio community and/or
B. To conduct technical investigations in all respects consistent with the Radio Regulations.

This means that we must have a secondary payload to accommodate this requirement. Still, this option seems far more promising than trying to get separate permissions from literally hundreds of agencies around the world.

The choice of frequency is thus limited to the AMSAT bands at 144, 435, 1215 and 2400 MHz. AMSAT has control over higher frequencies as well, but they are not really an option. If we are using the 3 m formerly present parabola at EMI, the ideal frequency is as high as possible, as lower frequencies lower the gain of the antenna. The antenna on the satellite will also be easier to construct, smaller and more efficient at higher frequencies. Also, the attitude control is affected, as a large antenna will give a drag that is comparable to the forces that are available for attitude control, meaning that a large antenna will make the satellite very stable, but only in one direction. On the other hand, lower frequencies means easier construction of the hardware, as it is possible to use standard components and PCBs when the dimensions of the circuit are significantly smaller than the wavelength. As none of us has constructed radio hardware before, this is an important argument. The lower frequencies also offer the possibility to buy economical and power-efficient single chip solutions. However, the 144 MHz band will need antennas of about a meter, which will be difficult to construct and fold around the very small satellite body, and will create a large drag force.

For these reasons, we have chosen to design for the 435-438 MHz amateur satellite band.

There are several potential additional benefits from using amateur radio frequencies. First of all, the radio amateur society is big enough to have Commercial Of The Shelf (COTS) equipment, both hardware, software and standards, which is a very big advantage compared to the amount of work it would present to build it for ourselves. Also, we have already had a lot of help in getting to know the vast field of radio communication. Another possibility is assistance if our own tracking and telemetry recovery fails.

However, there really is no such thing as a free lunch. As stated above, we need to provide some service to the community in return for these advantages. Several possibilities exist:

The most popular satellite function is the voice relay. It consists of a receiver and a transmitter retransmitting the received signals in another band. This enables two radio amateurs to talk to each other in real time over very great distances. However, to do this, we would need far more power, far more room and far more experience in radio transceiver design.

The satellite could function as a relay station for packet radio and facilitate communication in accordance with paragraph A. This could happen in different ways: a parrot relay, which transmits the packet back to the earth after a small delay, but covering a far wider area; or a store and forward BBS, which receives and stores packets until the receiver asks for them. However, both options are inconsistent with the power constraints, as we would have to power the transmitter for far more time than allowed by the power budget, and the receiver would have to stay on at all times. This could be avoided by limiting the duty cycle of the relay station or by reducing the transmitter power when in amateur relay mode.

Another solution is to make it possible for radio amateurs to contact the satellite. Either it could be possible to ping it and receive an immediate reply or, if power does not permit this, to store call signal and time of contact in a log and transfer this to the ground station for subsequent publication on a web site. This data could be used to map satellite amateurs worldwide and display the 'hot spots' on a map on the web site.

A variation could be to switch entirely to paragraph B and map general radio amateur activity worldwide. This could be done by logging the received strength signal from the radio in the 435 MHz band by building a (wideband) first mixer signal strength indicator.

Instead of a one-way uplink, we could implement a one-way downlink. In accordance with paragraph B, we could transmit test messages of falling signal strength, enabling radio amateurs to test the sensitivity of their receiving equipment.

We have spoken to AMSAT-OZ, the Danish branch of AMSAT, and they recommended implementing the last option given the constraints of the satellite. We have subsequently submitted a frequency application[6], endorsed by AMSAT-OZ, detailing our needs and what we have to offer, but has not yet received a definite answer. The last possible hurdle is the transmission permission for the specific hardware. AMSAT-OZ is of the opinion that the Danish Telestyrelsen (Communications Commision) should authorize the permit, while Telestyrelsen is of the opposite opinion. This issue has not yet been cleared, but should be as soon as possible.

Modulation Considerations

To transmit information, it is not enough to have a frequency. It is also necessary to modulate it in some way in order to transmit information. The simplest way to do this is OOK (On-Off Keying), switching the transmitter on and off. However, many more sophisticated and efficient modulation schemes exist.

Currently, the modulation issue has not been resolved as there are many different aspects to consider. As radio amateurs must be able to receive and understand the test transmitter we must comply with the modulation standard generally used among radio amateurs. This also makes the construction of the ground station easier. The bit rate possibilities differ between 1200 bps and 9600 bps where a possible configuration is that the 1200 bps will be used for the test transmitter and 9600 bps for the downlink.

The common modulations used by the radio satellite amateurs are PSK (Phase Shift Keying) or AFSK (Audio Frequency Shift Keying) for 1200 bps and GMSK (Gaussian Median Shift Keying) for 9600 bps. However the chosen chipset only supports simple FSK (Frequency Shift Keying) where the frequency shift of the nRF401 is fixed at approx. 25 kHz and the input voltage determines the RF2905's frequency shift. To use PSK will

[6] Which is found in the appendices

require extra hardware and raise the general complexity of the design. The question is whether the radio amateurs will be able to receive the 1200 bps downlink if we are using binary FSK or if we have to modulate it with two audio tones (AFSK)? It may be possible to do this without a digital-to-analog converter by using a RC low-pass filter on the formerly digital input, but this needs testing.

A second concern is the 9600 bps downlink, which are meant for raw data from the satellite. If radio amateurs in general should be able to understand this, we must implement the G3RUH[7] GMSK modulation[8]? The G3RUH is nearly universal standard when transmitting at 9600 bps. However it will not be easy to implement it into our radio design, neither hardware or software, it is doubtful if the computer has enough processing power and there is no room for extra hardware. A possibility is to include an onboard FPGA modem[9], which could take care of both 1200 bps AFSK and 9600 G3RUH GMSK, but this will add yet another big chip plus peripheral electronic to an already very heavy design – both conceptually and physically. This approach has a lot to say for it, however, as it takes away a lot of concerns. Using binary FSK, we will have to create our own modem on the ground; and we might create a lot of noise due to the high frequency components of the sharp edges. This might annoy others – and furthermore, it will make it more difficult to receive the signal on the ground station. On the other hand, we are adding a programmable, small geometry CMOS chip at a very crucial point of the satellite. A bit flip in the processor Flash memory might be taken care of by the bootstrap ROM and the radio in cooperation, but a bit flip in the radio will never be corrected.

Before any decision can be made, the capabilities of the radio satellite amateur's equipment must be uncovered, to see which modulations form they can receive and what they prefer. The decision however must be made as soon as possible, and will be on the top on the prioritised ToDo list in the upcoming course.

Link Budget

The link budget is a valuable tool for the designer in the design process of both the onboard radio and the ground station. The link budget describes the physical radio link between the earth and the satellite based upon information about orbit, satellite- and ground equipment and available power. Setting up the link budget in a spreadsheet enables the designer to adjust the different parameters to suit different hardware- and design possibilities/requirements and seeing the impact directly on the link calculations.
The two main results from the link calculations are the received-signal-strength, P_r, and the signal-to-noise ratio, SNR or E_b/N_o. The SNR indicates the quality of the received signal and is related to the bit-error-rate, BER. A high SNR gives small BER and vice versa. A relation between BER and SNR is seen below.

[7] Named for the call sign of James Miller, who designed the standard
[8] Details concerning the G3RUH standard see http://www.amsat.org/amsat/articles/g3ruh/g3ruh-index.html
[9]An interesting implementation is found on http://www.qsl.net/dg1scr/pr/yam/index_e.html

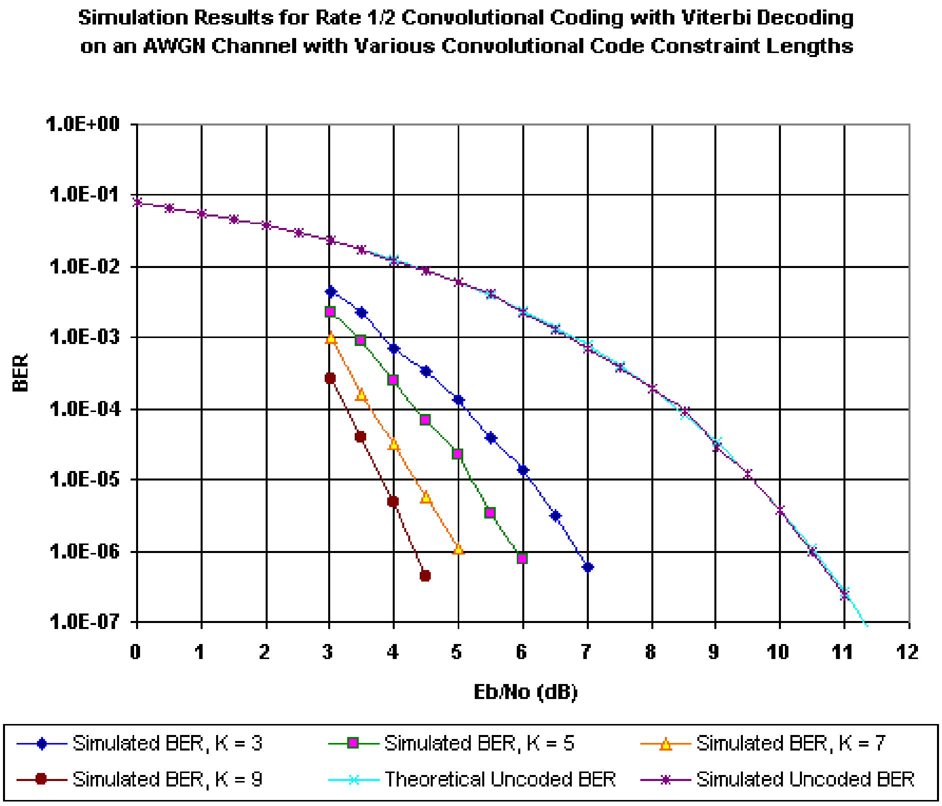

Figure 1 - SNR vs BER

As is seen on the figure, a SNR better than 11 dB is required to achieve a BER better than 1.00E-6, which is the minimum BER where error-correcting Hamming coding is no longer feasible given the size of the code, the packet size and retransmission time cost[10]. As long as the SNR remains high the received-signal-strength is of less importance since it is always possible to amplify the received signal using a low noise amplifier (LNA). So the optimisation process should be to maximise the SNR but at the same time keep an open eye on the received-signal-strength capabilities of the equipment is in focus. It may not be possible to put an extra LNA on the satellite.

Signal-to-Noise Ratio

The SNR calculations are based upon the following link budget equation:

$$E_b/N_0 = EIRP + G/T + 196.15 - 20\log(\frac{d}{1km}) - 20\log(\frac{f}{1MHz}) - 10\log(\frac{B}{1Hz}) \qquad [dB]$$ [11]

Where EIRP stands for "Equivalent Isotropically Radiated Power" or EIRP = P_t +G_t [dBW = dBW + dBi]. The P_t is the available power minus attenuation from the transceiver to the antenna, e.g. cable, connectors and the like. G_t is the transmitter antenna gain. G/T, which

[10] According to the Communication Protocol Group.
[11] From Flemming Hansens presentation used at "Satellite system and design course" summer 2001

defined as G_r - $10\times\log(T_{sys}/1\ K)$ [dB/K], pronounced G-over-T, is a measure of the quality factor or performance of the receiver. T_{sys} is the noise temperature of the receiver. It includes the noise generated by the receiver from the antenna to the LNA, but ignores the system noise after the LNA, as it is suppressed by a factor of the LNA gain. It takes into consideration the sky noise temperature, the system noise temperature and the LNA noise. The constant 196.15 includes 4π/c, Boltzmanns constant and the powers of 10 coming from using kilometres instead of meter for the distance and Megahertz instead of Hertz for the carrier frequency.

The distance, the frequency and the bandwidth are all included negative, which is also very intuitive as the SNR drops when they increase.

Received-Signal-Strength

The received-signal-strength calculations gives an idea about the quality of the hardware needed to received the signal. The calculations are based upon the following equation.

$$P_r = P_t+G_t+G_r-L_p \ \ [\text{dB}]$$ [12]

Where P_r is the received power, P_t is the transmitted power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain and L_p is the path loss equation.

$$L_p = 32{,}45+20*\log(d/1\text{km})+20*\log(f/1\text{MHz}) \ [\text{dB}]$$ [12]

Where the 32.45 dB contains the constant 4π/c as well as the powers of 10 coming from using kilometres instead of meters for the distance and Megahertz instead of Hertz for the carrier frequency.

Prerequisites

It is preferable to arrange the prerequisites according to the subsystem where they are used.

Global variables

Carrier frequency	435,2	MHz
Max Distance to Satellite	2830	km
Bit Rate	9600	bit/s
Sky Noise	150	K

The carrier frequency is not definite as the frequency application is currently being processed by AMSAT. The final orbit of the satellite is still unknown and depends on the possible launch opportunities, however a 600 km orbit is expected thereby resulting in a max distance of 2830 km. The bit rate of 9600 bit/s has been chosen, as this is the standard

[12] From Flemming Hansen and Olav Breinbjergs presentations used at "Satellite system and design course" summer 2001.

bit rate used by radio amateurs when communication with satellites. For this reason standard off the shelf equipment is available for the ground station.
The value of the sky noise is found in "The Radio Amateur's Satellite Handbook" and is a measure of the noise picked up by the ground antenna with a 5° elevation or the satellite antenna when looking at the earth.

Variables at Ground Station

Ground Station Transmitted Power	50	W
Ground Station Antenna Gain	19	dBi
Grund Station LNA Gain	20	dB
Grund Station LNA Noise	1	dB

The ground station transmitted power is limited by the proposed transceiver, to further raise this would requires an expensive amplifier and has therefore been rejected.
The antenna gain is based on an array consisting of two X-Yagi antennas each with a gain of 16 dBi with 3 dB gain by the doubling of the elements.

Variables at Satellite

Power output at PA terminals	0,5	W
Satellite Antenna Gain (Antenna Group)	-3,18	dB
Satellite reflection coefficient (antenna), Γ	0,2	
Satellite Antenna loss (ohmic loss)	0	dB
Satellite LNA Gain, MAX2640	15	dB
Satellite LNA Noise, MAX2640	1	dB

The satellite available power is the 0.5 W from the power amplifier output terminals. The satellite antenna gain and the antenna reflection coefficient are obtained from the antenna group. An antenna loss or attenuation has been added for future corrections if any should arrive at a later point in time.
The accepted power accepted by the antenna is then calculated as $P_{ac} = P_{av}(1-\Gamma^*\Gamma)$

Constants

Reference Noise Temperature - Earth	290	K
Reference Noise Temperature - Satellite	320	K

Attenuation of Semirigid SMA Coax Conn.	0,025	dB

Aircom Plus Cable performance - 435 MHz	0,08	dB/m

The reference noise temperature on earth is found to be 290 K by looking in different literature.[13] The noise temperature on the satellite is still unknown as no thermal calculations has been made. An arbitrary value of 320 K equivalent to 47 °C has been chosen.
Flemming Hansen has proposed the attenuation of the SMA connectors and no corrections has been added. The cable has been chosen due to its low attenuation, which was necessary due to the possible placement of the transceiver, which adds approx. 50 m of cable.

Results

Based upon the above prerequisites the signal-to-noise ratio and received-signal-strength can be calculated and the results are:

Satelite to Earth – Downlink

SNR, Eb/N0	**21,22430515**	**dB**

Received signal strength before LNA	-141,6270941	dBW	-111,6270941	dBm
After LNA	-121,6270941	dBW	**-91,62709407**	dBm

Earth to Satellite – Uplink

SNR, Eb/N0	**36,41904583**	**dB**

Received signal strength before LNA	-127,0798064	dBW	-97,0798064	dBm
After LNA	-112,0798064	dBW	**-82,0798064**	dBm

The calculations for received signal strength include any attenuation from the transceiver to the antenna

Downlink
The signal-to-noise ratio of 21 dB must be said to be satisfactory. If compared to Figure 1 a SNR of 21 dB will give a BER that is off the chart, meaning much better that 1.00E-6 which was the minimum requirement from the protocol group. The proposed transceiver, the Yaesu FT-847, has a sensibility down to approx. –120 dBm and according to the link budget the minimum received signal after LNA is approx. –91 dBm. This leaves us with a buffer of approx. 29 dB for the current configuration, which should be enough. In case of any unexpected or unforeseen attenuations an extra LNA could be installed to give a further 20 dB gain.

Uplink
On the uplink side the SNR is even better, the result of 36 dB is partly due to the fact that we are transmitting with 50 W and partly because of the high gain of the antenna array.

[13] The Radio Amateur’s Satellite Handbook

However it is also preferable to have the better SNR at the satellite, as the onboard radio cannot be upgraded or repaired if deterioration should occur. The received-signal-strength is approx. –82 dBm. This is somewhat closer to the maximum sensibility of the proposed onboard transceivers of approx. –100 dBm though still giving us an 18 dB gap. It should also be taken into account that the expected BER increases as the received signal near the maximum capabilities of the transceivers

Based upon the proposed ground station and satellite configuration the link budget looks good. The signal-to-noise ratio should ensure that the bit-error-rate in the received signal could be neglected, the protocol should catch any corrupted packages and resent them. However it would be preferable to have a larger margin in the received-signal-strength at the satellite. This could be accomplished by either increasing the power output at the ground station or implementing another low noise amplifier in the satellite radio. The same approach could be used if the received-signal-strength at the ground station turn out to be too small, but this should not necessary according to the calculations.
In this link budget the impendence mismatch between the satellite antenna and radio has been taken into account, but any mismatch at the ground station has not. This is due to lack of data, which hopefully should be generated later this year, but mismatch is expected to be small, $\Gamma < 0.2$.
The link budget does not take into account any polarization mismatch due the orientation of the satellite, but as we are using circular polarization and are including a polarization switch on the ground station, this loss is limited to maximum 3 dB.

For further detail see the full link budget.[14]

Interfaces

Interface towards Computer

The interface between the radio and the rest of the satellite is a number of parallel control lines, two serial data lines, and a number of analog data lines. All intelligence is placed in the onboard software, except the logic controlling the autonomous beacon. All control signal levels are CMOS at the computer voltage with true polarity. The total electrical interface diagram is found in the appendix.

Two input lines are needed for enabling the transmitter and the receiver. If these lines are high, the corresponding device will be turned on. To avoid extra circuits on the radio board, the polarity of this interface might change depending on the chipset selected. The radio will provide pull-up or pull-down resistors and series resistors ensure correct function at start-up, where the computer outputs are tri-stated.

One input line is needed for detecting if the onboard software is functioning. This line should be inverted every 100 ms. If this signal is not detected, the radio will change to beacon mode, autonomously sending out a PWM signal relaying two analog measurements, e.g. the battery voltage and radio temperature.

[14] **DTUsat link budget.xls** at the www.dtusat.dtu.dk

The radio is responsible for translating a serial binary bit stream from the computer into a radio signal. The received radio signal is translated into a serial binary bit stream and sent to the computer. The interface is CMOS with true polarity - high for mark, low for space. No detection of start- and stop bits is provided. This part of the interface is likely to change radically depending on the final choice of modulation, e.g. do we need a dedicated modem or is binary FSK sufficient.

An analog line from the radio contains information on the received signal strength. The format and voltage on this line will depend on the chipset used and is undetermined at this time.

Interface towards Antenna

The radio signal to and from the antenna will be available by a 50 ohm SMA connector. This socket will be soldered on the radio circuit board. If necessary, the antenna group provides a feeder network, but room for implementing it may be available on the radio PCB. If this is the case, we will use a line of 50 ohm impedance, but skip the SMA connector.

Interface towards Power System

The radio interface towards the power supply is one low noise 3.3V line for the chipsets and one unregulated line for the power amplifier. We will provide a switch-mode step-down converter for the PA and shut down all operations – including the beacon – if the voltage on the unregulated bus drops to dangerously low levels (less than about 3 volts) to protect the battery from damage. One line out is connected to the emergency common open-collector latch-up line that will inform the power supply that we have a latch-up and it will shut down the entire satellite and reboot it.

Mechanical Interface

The radio will fit on one PCB, which should be standardized across all modules. The specifications for this are being done in the Mechanical Engineering Group and the active area for components is around 6x6 cm and max 1 cm high. The evaluation boards we have made for the transceivers seem to fit within these specifications, but including all peripheral electronics the board will be very full. To maintain good electrical characteristics, 4-layer boards may be necessary.

Electromechanical Interface

Connectors should be standardized across all modules. So far the Mechanical Engineering Group has proposed that we use a common bus system in one end of the PCB so that we can plug the PCBs in and out of the satellite if we wish. Suggestions have been made on either IDC connectors or the ones similar to those that are found on e.g. the ISA bus in a PC. This issue will be resolved soon.

Thermal Interface

The thermal interface still has to be designed. The largest power dissipator in the satellite is the power amplifier with a power loss of up to 500 mW. Practical experiments have to be done to verify if this raises any problems with our current design. In case of overheating we have to consult the mechanical group to common seek out a solution that will solve this problem if it occurs. For more information, see the environment section.

Transceiver Design

The radio hardware is at the current moment still at prototyping level where the selection of the components still has to be concluded and subcircuits still need to be designed. The flowchart of the complete radio transceiver is shown below.

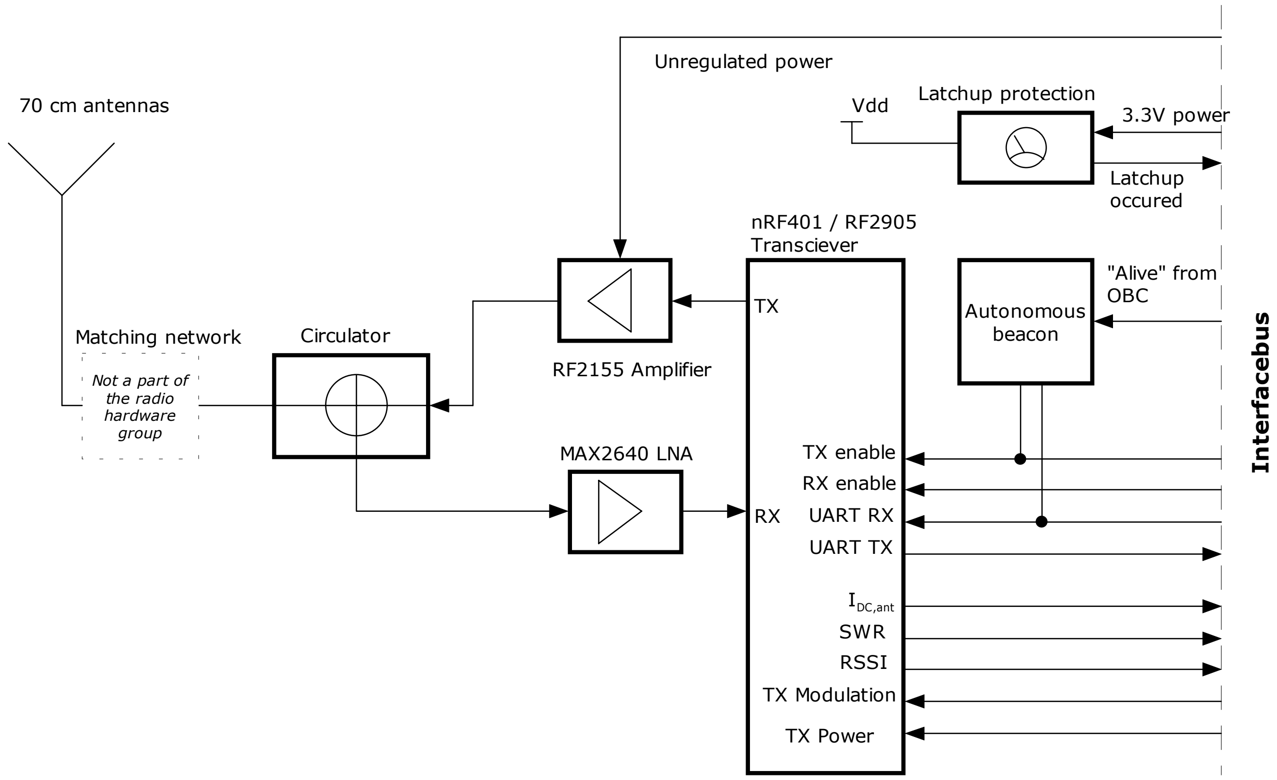

Figure 2 – Block diagram of the functional elements in the radio transceiver

Due to the size of the antenna on the satellite, the frequency that has been chosen is placed the 70 cm amateur band. This means that our radio hardware much be able to operate within frequencies that lie between 435 MHz and 438 MHz. In our link budget we have chosen the output power from the satellite to be 0.5W which will give us enough signal strength on earth to receive it with a couple of yagi antennas on top of the roof on the EMI building while staying within the power budget for the entire satellite. Taking these parameters into consideration we have put a trade-off map together with the possible chipsets that we have found at different semiconductor manufacturers.

Possible Transceivers

Chipset	nRF401	nRF903	RF2905
Supplier	nordic VLSI	nordic VLSI	RF2905RF micro devices
Diverse information 1	Good manufacturer contact	Good manufacturer contact	Good documentation
Diverse information 2	Eval. board, chips at hand.	Avail. in november	Good documentation
Single chip (internal PLL, filter)	X	X	X
Transceiver/receiver/transmitter	Transceiver	Transceiver	Transceiver
Frequency span	433 MHz +- 5%	430-950 MHz	300-1000 MHz
Package	20 SSOIC	32 TQFP	48 LQFT
External components	15 + matching network	15 + matching network	**"50"**
Programming necessary	None	**SPI, 14 bit**	None
Voltage	2V7 – 5V2	2V7 – 3V3	2V7 – 5V
Standby mode, mA	0.008	0.2	0.001
Receive power, mA	"11"	18.5	"9'
Transmit power, mA @ dBm	8 @ -10,	31.5 @ 10, 16 @ -8	25 @ 10, 10 @ -8
Transmitted power, dBm @ 50 ohm	"10 - loss in network"	"10"	10, analog adjustable
Antenna / output	Loop push-pull / 400 ohm	Loop push-pull / 180 ohm	50 ohm, separate TX/RX
Flight proven / technology	No, BiCMOS on Si	No, BiCMOS on Si	No, BJT on Si
Operating temperature, celcius	"-25 – 85"	-40 – 85	-40 – 85
Modulation	FSK	GMSK/GFSK stable	ASK, FSK, OOK
Data rate	Max 20 kbps	Max 76.8 kbps	-
Sensitivity, dBm	-105 @ BER 10-3	-100 @ BER 10-3	-100 @ 8 SINAD
Standard oscillator for 435 MHz band	No, a bit over 4 MHz	No, a bit over 4 MHz	No, a bit over 6.5 MHz
RSSI output	**No, not possible**	No, possibly from filter	Yes, analog, 25 mV/dB
Conclusion	Able to comply with our demands except no RSSI output.	To demanding control logic needed.	Large functionality but needs lots of external components.

Chipset	RX5000	TDA5100	TDA5210
Supplier	RF monolithics	Infineon	Infineon
Diverse information 1	X	X	X, external 10.7 MHz filter
Diverse information 2	Receiver	Transmitter	Receiver
Single chip (internal PLL, filter)	433.92 MHz	433-435 MHz	433-435 MHz
Transceiver/receiver/transmitter		16 TSSOP	28 TSSOP
Frequency span		10 + matching network	"20"
Package		None	None
External components	2V7 - 3V5	2V1 - 4V	**4V5 - 5V5**
Programming necessary		0.00025	0.0001
Voltage		N/A	"7.5"
Standby mode, mA		7 @ 5	N/A
Receive power, mA		"5"	N/A
Transmit power, mA @ dBm		Single-ended	Single-ended

Transmitted power, dBm @ 50 ohm		No, bipolar on Si	No, bipolar on Si
Antenna / output	"-40 - 85"	"-25 - 85"	"-25 - 85"
Flight proven / technology	**OOK**	ASK/FSK	ASK/FSK
Operating temperature, celcius		Max 100 kbps	Max 100 kbps
Modulation		N/A	"-100 @ BER 10-3
Data rate			No, a bit over 6,7 MHz
Sensitivity, dBm		N/A	Yes, Peak detect
Standard oscillator for 435 MHz band	Rejected due to OOK modulation only	Only a transmitter	Rejected due to too high supply voltage needed.
RSSI output			
Conclusion			

Chipset	MC13176	MC13136
Supplier	Motorola	Motorola
Diverse information 1		
Diverse information 2		
Single chip (internal PLL, filter)	X	**External PLL, external filters**
Transceiver/receiver/transmitter	Transmitter	Receiver
Frequency span	250-470 MHz	200 MHz
Package	16 SO	20 SOIC
External components	"15"	"25"
Programming necessary	None	None
Voltage	1V8 - 5V	2 – 6V
Standby mode, mA	0.0005	Not possible
Receive power, mA	N/A	3.5
Transmit power, mA @ dBm	34 @ 10	N/A
Transmitted power, dBm @ 50 ohm	"10"	N/A
Antenna / output	50 ohm	50 ohm
Flight proven / technology	Space-proven, Mosaic 1.5, BJT on Si	Space-proven, Mosaic 1.5, BJT on Si
Operating temperature, celcius		
Data rate		9600 bps
Modulation	FM/AM	**AM**
Sensitivity, dBm	N/A	1 uV @ 12 SINAD
Standard oscillator for 435 MHz band	No	-
RSSI output	N/A	Yes, analog
Conclusion	Rejected to too little functionality.	Rejected due to AM modulation only.

From the trade-off map we have chosen the nRF401 and RF2905 chipsets to work with since these two meets our requirements in form of functionality and complexity. The main difference between them was that the nRF401 do not had RSSI output and adjustable output power which the RF2905 has, and that the nRF401 only supports binary FSK

modulation, but in its disadvantage is the need for three times as many external components and some of them are exotic types which are not easy to come by.
Both chipsets are able to do FSK modulation, but at the present point the kind of modulation used has not been chosen. If we choose to use nRF401 chipset we are forced to use binary FSK modulation, but if we choose to use the RF2905 chipset we are capable of using almost any kind of modulation except PSK. This will be useful if we choose to use the G3RUH modulation form suggested in the modulation section.

None of the chipsets have enough output power to supply the 0.5W transmitted power that is needed in our link budget. Therefore we have placed a power amplifier to boost the signal after the transceiver. The possible choices are put together in a small trade-off map.

Chipset	RF2104	RF2117	RF2155
Supplier	RF microdevices	RF microdevices	RF microdevices
Frequency span	400-1000 MHz	400-500 MHz	430-930 MHz
Voltage	2V7 - 3V6	3V - 5V5	3V – 5V
Standby mode, mA	0.01		0.01
Transmit power, mA @ dBm	"400"	"1300"	"500"
Transmitted power, dBm @ 50 ohm	"27"	"33"	"27"
Gain, dB	"26"	"33"	"31"
Efficiency	"40%"	">50%"	"60%"
Package	CJ2BAT0 (16 SO)	16 PSOP with heatsink	BAT-wing (12 SO)
External components	"12"	"15-20"	"15"
Gain adjustment	No	No	Yes, 2 digital pins
Antenna / output	50 ohm	50 ohm	50 ohm
Flight proven / technology	No, BJT on Si	No, GaAs HBT	No, GaAs HBT
Operating temperature, celcius	"-40 - 85"	"-40 - 85"	"-30 - 85"

Here we have chosen the RF2155 chipset due to its functionality and very high efficiency. The option of decreasing the transmitted power by programming the chip will later be in much need to fulfil the requirements on operating on the radio amateur band and therefore be much helpful. It is an option that none of the other chips have. Since we operate in vacuum in space heat transfer from the chips might turn out to be a problem and therefore RF2155's high efficiency will probably help us in making our final design.

Our link budget shows that the received signal strength in the satellite is too low for the transceiver sensitivity, and a low noise amplifier (LNA) is needed to pre-amplify the signal before it reaches the transceiver. A LNA, MAX2640, from Maxim IC was chosen, but we still need to test it and see if it fulfils our requirements.
None of our choices in selected chips have included the fact whether they have been flight proven or not. Some of the technologies they use have the reputation of being radiation sensitive, and a total dose radiation test have been completed on all the chips we intended to use in our design. The results from these tests are currently not available because they have not been mounted and tested in a circuit yet. But we do hope that the RF2905 will

work longer then the nRF401 since the former is built on BJT[15] technology, where as the nRF401 is built on BiCMOS[16] that have a reputation of being more sensitive to radiation.

Design

The two manufacturers, Nordic VLSI and RF microdevices, of the chosen transceiver chipsets was contacted with the hope of receiving evaluation boards. Nordic VLSI sent us two boards together with three small application boards and a rod of 50 IC's. RF microdevices wanted $300 for their evaluation boards so we chose to build our own evaluation board based on the design from their homepage and ordered 25 transceiver IC's instead.

The two test boards were designed so that we can test the transceiver chipsets alone without the LNA, power amplifier and beacon. This have been done to evaluate the radiation test and our skills in manufacturing our own boards since, if we are not capable of making a simple evaluation board with acceptable performance, there are not much hope that we can make a complete radio function.

Both evaluation boards are based on the design found on the manufacturers homepages. We had to make different layouts because we are not able to work with too small SMD components and only have the opportunity to work with two layer PCB.

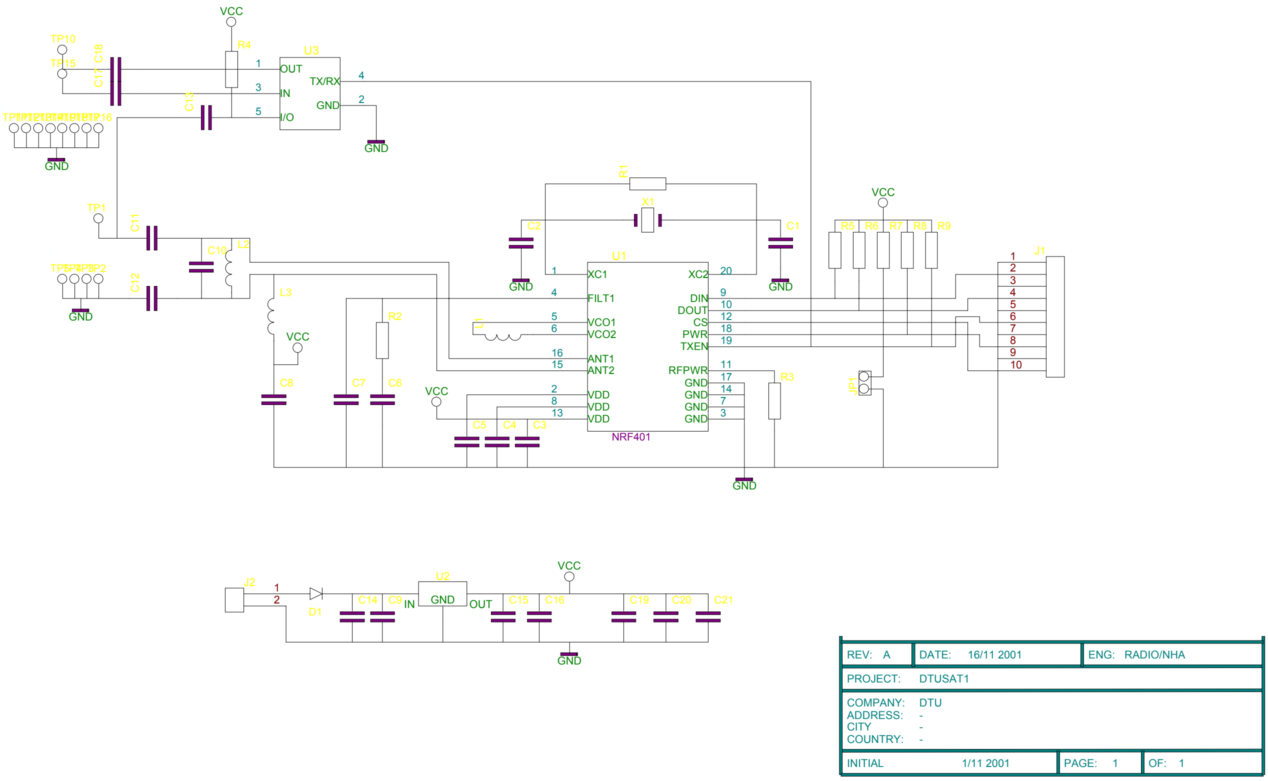

Figure 3 - Schematic of nRF401 evaluation board

The nRF401 schematic shows the nRF401 transceiver with a RF2436 switch, which is included to be able to split the signal on to two separated connectors – one for only the

[15] Bipolar Junction Technology
[16] A mixture of CMOS and bipolar technology on the same chip

received signal and one for only the transmitted signal. All of the components used are easily obtained from local distributors.

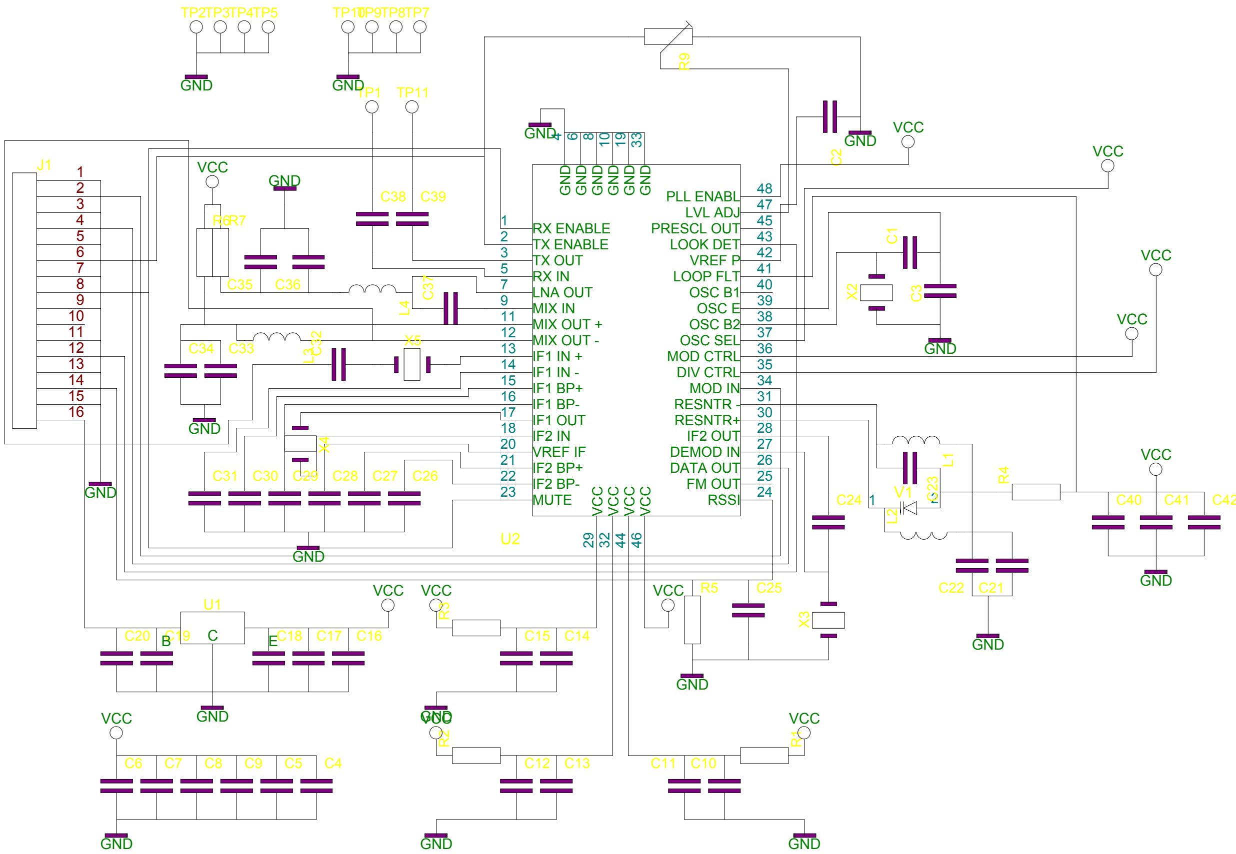

Figure 4 - Schematic of RF2905 evaluation board

The schematic above shows the RF2905 transceiver in its evaluation setup. We have the possibility to test all functions of the chip and manually set the output power level. In the selection of the components we have chosen the recommended from RF Microdevices, which turned out to be a problem since we had a hard time obtaining some of them. The varactor diode were only available in large quantities, so we had to replace is with one from another manufacturer with similar characteristics. We were able to get a small amount of samples from our local distributors.

Peripherals Design

To enable the radio-transceiver to be able to transfer data to and from the earth, some peripheral electronics is needed.

- **Power Amplifier:** To raise the power level from the 10 mW at the transceiver to a signal capable of carrying the information to the ground, a power amplifier, RF2155, has been selected. However, the impedance matching networks and the bias circuits have not yet been designed.

- **Low Noise Amplifier:** To raise the incoming power level above the receiver noise floor, a low noise amplifier, MAX2640, has been selected. However, as for the power amplifier, the impedance matching network has not yet been designed.

- **Separation of antenna signal:** To separate the output level from the power amplifier from the LNA, a circuit is needed or else the LNA will retire prematurely because of the high level present on its input. We have tried to look after a switch that will meet our requirements, but those we have seen either does not work in our frequency range, does not tolerate the power, or else does not attenuate the signal from the power amplifier enough. The current design possibilities are a monolithic switch, a circulator as shown on the block diagram, or a discrete PIN-diode circuit.

- **Modulation network or possibly a modem:** To transmit and receive information to and from the earth, it might not be good enough to use binary FSK. If more sophisticated modulation is used, we will have to design it. If the computer is powerful enough, the modulation network might consist of a digital-to-analog converter driven by the CPU – however, we also need to decode the uplink data.

- **Autonomous beacon:** Listens to an "alive" signal from the OBC that should be inverted every 100 ms to indicate that the computer is running. If this does not happen, it should start the radio transceiver and send a signal each minute that contains information on the battery's temperature status. It will provide the ground control some information on why the OBC is not up and running. This will mean that the mission is not wasted completely if the OBC is killed during launch and we still have some degree of success.

- **Step-down converter:** The power amplifier draws its supply directly from the battery, which means we get the voltage unregulated with the voltage depending on the charge of the battery and the incident sunlight. The power group estimates that this can range from 2.6V to 6.5V, which means sometimes the voltage gets too high for the power amplifier to operate, sometimes too low. Therefore a step-down converter has to be designed to ensure that we have the proper voltage level at all times. Furthermore the step-down converter must also have an under-voltage lockout circuit to switch off the power amplifier if the battery supply charge gets too low and the rest of the satellite is in danger of not being able to operate if we continue to transmit our beacon or data signal. Using a step-down converter also makes us able to supply the power amplifier with just the right voltage level where it gives us the best performance level in terms of efficiency.

- **Latch-up protection:** To protect the radio if some part of our radio suddenly experiences a latch-up, a latch-up protection circuit is included in the design. If a latch-up occurs we have to inform the power supply and it will reset the complete satellite. This function can be realized by using a monolithic measuring amplifier that measures the current draw by measuring the voltage across a small measurement resistor placed in series with the power line. This will indicate to the power supply when the current is getting to high. There must be separate latch-up protection for the 3.3V supply and the power amplifier supply.

- **DC measurement of the antenna current:** A circuit to measure the DC voltage on the antenna is needed to supply the tether group with information on how the satellite is working in the plasma. This can be done by AC-isolating the antenna feed line from a measuring resistor using an inductor.

- **SWR:** If one of the antennas have been broken off during launch a SWR meter might be constructed to ensure that we will not kill the power amplifier when we transmit. The SWR information is used to turn down the output power to an acceptable level so that the reflected signal is not strong enough to kill the amplifier. This level of protection is not likely to be included.

These functions have not yet been designed but preliminary research has been done and at least the critical functions will hopefully be completed during the spring of 2002.

Functionality Tests

To verify the functionality of the produced transceiver test prints we have made a computer interface PCB to communicate and test the selected transceiver chipsets.

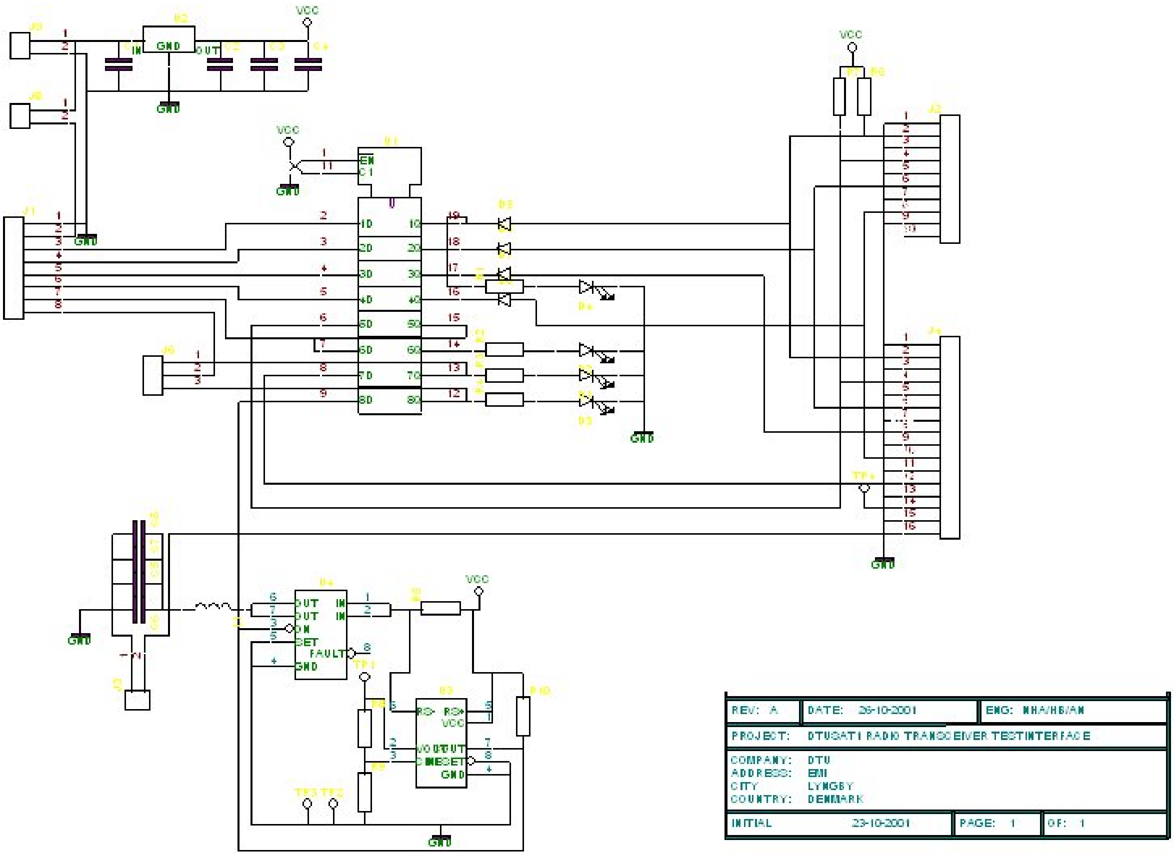

Figure 5 - Schematic of the computer interface

It consists of a transparent latch, 74HCT573, connected to PC's parallel port and the datapins on the transceiver PCBs. A voltage regulator supplies the chipsets with power and a current switch, MAX890, makes us able to perform a latch-up protection by switching off the load if the current is above a set point. The switch is controlled by a current-sense amplifier, MAX4373, that senses the current by measuring the voltage drop across a series resistor. To finish off the design some LEDs are placed as indicators.

The circuit has been tested using a small program controlling the parallel port, written in Pascal. A more specific program is needed for the actual tests. The program needs to be able to control both the transmitting and the receiving end at once to test the transmission quality. The rest of the functions are controlled by hardware settings and transceiver performance is measured using a spectrum analyser. Some of the tests that needs to be done includes BER, signal strength and spectral analyse.

At some point, a long distance transmit and receive test should be carried out using a model of the satellite antenna and the real ground station. This will enable us to test modulation and give a more real performance measure for the entire system.

Satellite Environment

The space environment is not very kind on anything. Especially electronic systems are vulnerable to the conditions. Among the factors affecting the operation of the on-board electronics are, apart from the factors that can destroy the physical boards and components, the vacuum, temperature and ionizing radiation. The physical dangers as micrometeorites, plasma and free radicals will hopefully be stopped by the mechanical part of the satellite – the outer shield. Inside the satellite, different modules must coexist on very little power and very close to each other. But first, before we even reach space, the satellite will have to withstand the harsh ride on top of a former Russian missile launcher.

Launch vibrations

The Russian Dnepr launcher, which is the most probable launch vehicle, is no Cadillac. The spectrum of acceleration when launching shows 7.7 G acceleration with several G vibration, and with strong Fourier components at up to 1000 Hz when the separation bolts explode. The problem is to keep all resonance frequencies above the spectrum of the rocket to avoid that the satellite is shaken to bits inside the launcher. As electronic components are very light and are very tightly bonded to a very sturdy epoxy board of a smallish size, this is not a serious problem for us. The only limitation is to ensure that the solder joints are correctly done. It is important that all components have the chance of giving in a little bit, as the board will of course flex a little and stress the components through their joints. For this reason, it is not wise to use big BGA[17] packages in space, but to use leaded through-hole or leaded surface mount components. However, we are quite certain that the PCBs will keep together if the structure that supports them does.

Satellite electrical noise

The different satellite modules will be potentially very annoying to each other. E.g., we have to pick up and decode signals measured in microvolts while sitting right next to a microprocessor, radiating plenty of harmonics in the same band. The other way round, we have a radio transmitter pumping out half a watt to an antenna and drawing a full watt from the power supply at the same frequency, while the attitude control system is trying to measure the magnetic field. This is bound to cause some interference problems, which must be taken seriously before attempting to integrate the satellite. We plan to filter the incoming power extensively, both inductive and capacitive. This will help everybody to get cleaner power. We are thinking of shielding the critical parts of the circuit using grounded copper foil, but are not yet sure if this will be effective or ruin our own circuit behavior. A simple thing, which should be done, is choosing the microprocessor clock frequency to keep the harmonics as far away as possible from the operating frequency.

Space debris

When moving at several kilometers per second, bits of material massing just a few milligram will have a kinetic energy that is big enough to destroy the satellite no matter what we do, but fragments of this size are – luckily – quite rare, and the probability of getting hit within the service time is very low. But even the smaller particles,

[17] Ball Grid Array, a package where the solder joints are distributed over all of the bottom area of the package. This makes the bond between component and board very solid and stresses the board tremendously at the corners of the package.

micrometeorites, are a real danger, but the mechanical team have devised a two-layer honeycomb structure that will shield the insides of the satellite from most of them by making the outer layer evaporate the incoming particle and the inner layer stop it. By doing this, the total mass of a structure that is able to stop particles of the sizes that are likely to hit us is significantly lower than the mass of a solid structure able to do the same job. If a particle nevertheless penetrates the satellite skin, the insides will be sprayed with a mixture of molten aluminium and molten whatever-that-particle-consists-of, which is likely to short out the electronics. We hope that the outer shield will protect us from this danger.

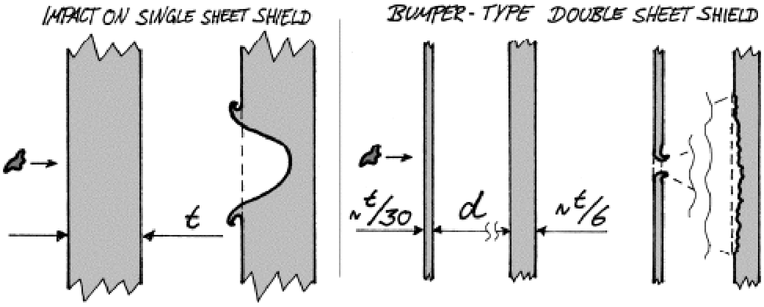

Figure 6 - Two different strategies in protecting the satellite from micrometeorites. [18]

The group that designs the structure, MEG, has calculated that this structure should be able to withstand particles up to circa 0.1 mg[19] to have a decent probability of staying alive. By using the bumper-type shield, the weight of the structure can be reduced considerably while maintaining the protection. However, the protection against radiation is only dependent on the amount of material and is thus worse with the bumper shield. It is currently unknown what damage the solar panels, that will naturally be attached to the outer surface of the shield, will suffer from the micrometeorites, but as solar panels are space-proven, they seem to work anyway.

Plasma and radicals

The plasma trapped in the earths magnetic field is charged and conducting and would disturb electronics exposed to it. Luckily, the plasma is moving in spirals because of the magnetic field, and as charged particles recombines at a conducting structure, and as the satellite body is made from aluminium, the plasma will not come close to the printed circuit boards. The plasma recombines on the surface and this effectually creates a plasma-free zone of a few centimeters around the satellite. However, depending on our actual orbit, it is possible that outer elements – such as antennas – will collect electrons and accumulate a negative charge. If these elements are not grounded (if one can speak of grounded in a satellite hovering 600 km above the earth) internally, they will charge until they spark or the voltage exceeds the rating of the components connected to the antenna, possibly destroying the component or, at the very least, generating a lot of electrical noise. We will DC-couple the antenna to ground to avoid this problem.

Free radicals are atoms stripped of their outermost electrons. They are present in the traces of atmosphere around the satellite, and are very corrosive. They will primary pose a problem to the outer structure, but as the satellite has holes in it, they will diffuse into the

[18] Illustration from MEG presentation
[19] MEG report and presentation at DTUsat webpage, http://www.dtusat.dtu.dk

body and possibly erode the electronics, as well. This factor will probably not be the worst danger facing us, as the gas molecules are quite rare and are likely to react with a part of the inner structure before getting to the electronics itself.

Vacuum

Vacuum means that cavities in the molten components are suddenly pressurized compared to the surroundings. This can lead to fractures and broken bonding wires. Also, materials as lead, some plastics and other normally solid and durable materials find that the pressure of the surroundings is smaller than their steam pressure and boil away. Finally, the thermal properties of a system changes dramatically as convection cooling disappears. We will have to test our components in vacuum to ensure that they will not break up or boil. Today, leadless solder is a standard, so that will probably not pose a problem.[20]

Temperature extremes

The temperature equilibrium range for a body in space is quite large. The temperature when the satellite faces the sun with its maximum area and the earth with the rest can climb to about 80 degrees, while the temperature when the satellite in the earths shadow and has the minimum area facing the earth, the temperature equilibrium can be as low as -40 degrees[21]. The temperature rating for normal, commercial components are typically 0 to 70 degrees, for industrial or military components typically about -40 to 85 degrees[22]. Outside these temperatures, the manufacturer does not guarantee that the epoxy coating and the silicon chip will stay together, and the glue or the bonding might be damaged. Special components in the satellite, such as the batteries, the camera chip and the high power components, have more critical demands on the temperature.

High power components are sensitive to high temperatures, as their cooling efficiency decreases as the temperature difference between the chip itself and the surroundings drops. Thermal management is handled by calculating the thermal resistance from the chip to the ambient temperature. A silicon chip can withstand temperatures up to about 150 degrees, some power components up to 200 degrees, above which it is permanently destroyed. At high temperatures, the doping materials diffuse faster, decreasing the lifetime of the chip, but this is of no great concern in this application. To keep the temperature from exceeding the absolute limits, the power dissipated and converted to heat in the chip needs to be conducted away from the silicon dice. The rate at which this happens [W] depends on the thermal resistance from the chip to the ambient reservoir [K/W] and the temperature difference between the chip and the reservoir. By multiplying the dissipated power by the thermal resistance, the temperature difference can be found. The different heat transfer paths are shown below.

[20] According to Bo Brændstrup, EMI at Ørsted-DTU, the feeder networks for the Danish Ørsted satellite were constructed and soldered at EMI no different from any other PCB.
[21] Calculated by the camera group – in part verified (as the power consumption is different) from the Japanese group at the Tokyo Institute of Technology – http://horse.mes.titech.ac.jp/srtlssp/cubesat/index.html
[22] Datasheets for several different components

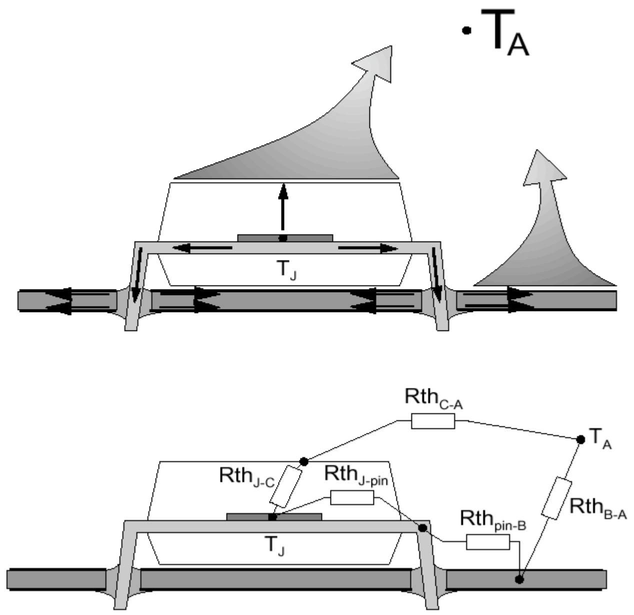

Figure 7 - Most important thermal resistances shown with a DIP package[23]

It is clear that a higher ambient temperature will make the heat transfer less efficient, making the chip heat up until a new equilibrium is found and thus track the surroundings in temperature. That is, if the chip dissipates a lot of power, it will not be able to get rid of it if the ambient temperature is too high.

This is commonly expressed as a power derating – that the maximum permissible power is lower at higher ambient temperatures. The power amplifier (PA) in the radio is the satellite component dissipating the most power. When fully loaded, it will dissipate about 500 mW, which will raise the chip temperature to some point[24]. Unfortunately, the datasheet for the RF2155 does not give these numbers. However, we have found data from other power components using the same package style – 12 pin batwing power SMT (SO-12):

[23] Illustration from http://www.njr.co.jp/pdf/ee/ee05007.pdf

[24] Datasheet for RF2155, 500 mW RF PA, digital adjustable gain, 60% efficiency. The PA stage is not designed yet.

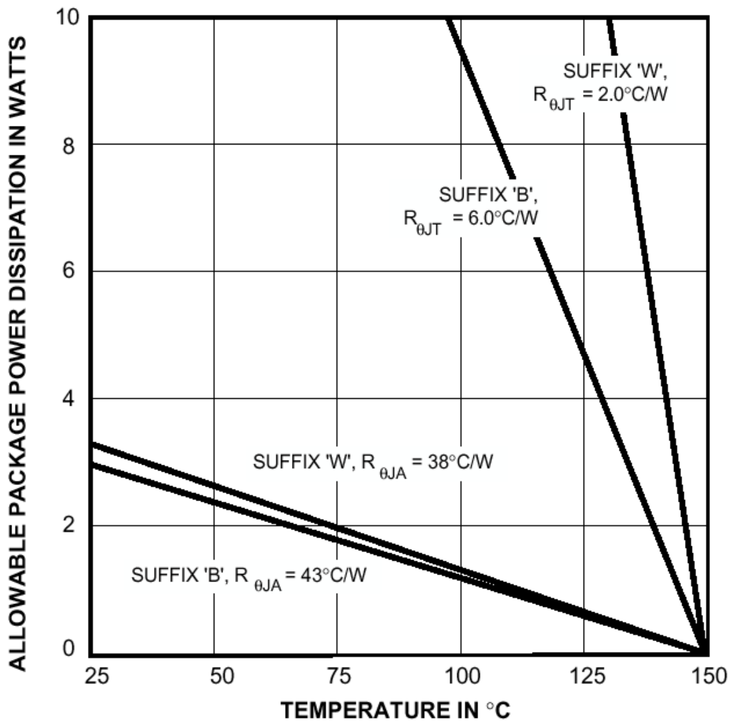

Figure 8 - Derating a SO-12 batwing with 6 square centimeter copper area at the batwings at atmospheric pressure. The batwing used in our PA is suffix W. [25]

Given that the junction-to-pin, $R_{th,junction\text{-}pin}$, is approximately the same for the two different chips[26], the dissipation of 500 mW does not seem to be a problem as long as $R_{th,pin\text{-}ambient}$ is kept down. If it is possible to connect the copper area to the satellite structure, the temperature will not be a problem for the PA. It is, however, difficult to predict what the precise efficiency is from the datasheets due to the fact that convection cooling, normally by far the most efficient cooling mode, is not possible in space – it has no medium. All heat must be transferred away from the chip using conduction or radiation. If it proves impossible to reach the necessary efficiency in the power transfer, a possibility is to add thermal inertia near the power amplifier, as it will not be used for long continuous periods of time.

The camera chip is also temperature sensitive. The thermal noise in the pictures naturally rises with the temperature, and CCDs that are used for long-time exposures are routinely cooled to very low temperatures. Active pixel sensors work differently, and often do not work at low temperatures at all, while their already high pixel noise gets even higher at high temperatures. Additionally, the camera has to be exposed to the thermal radiation of space in order to be able to capture pictures of it, further increasing the thermal design difficulty.

Last, but not least, the batteries depend on chemical reactions to function. At low temperatures, the chemical reactions are slower, while the contents of the battery might be destroyed at high temperatures. The technology used is Lithium-polymer, which has a

[25] Illustration from datasheet for Allegro A3951 motor driver at http://www.jlab.org/accel/eecad/pdf/3951.pdf
[26] Which is almost certainly not the case, as it depends on the placement and design of the chip inside the package. However, it is not likely that the difference is more than a factor of 3, which is needed to drop the allowable package dissipation below 500 mW at 85 degrees ambient.

typical temperature rating of 0-30 degrees – by far the tightest in the spacecraft. We will not be able to keep the whole spacecraft within these limits, so the battery will need special care. One possibility is to isolate it using multi layer isolation, an isolating material utilizing the lack of convection in space to achieve a very light and extremely isolating sheet, and provide active temperature control with a temperature sensor and a small heater. Still, the battery will probably be the most critical component in terms of thermal design, as it is very sensitive and very important to keep working.

Ionizing radiation

The last of the special dangers present in space is radiation. On the earth, we are protected from ionizing radiation by a combination of the magnetic fields and the atmosphere, but in space, the protection from natural causes is much lower. Luckily, our orbit will lie below the worst of the Van Allen belts, so the satellite will be largely shielded. However, the annual radiation dose to the electronics will still be far higher than on the ground. This diagram shows the annual radiation dose broken down in composants as a function of the aluminium shield thickness.

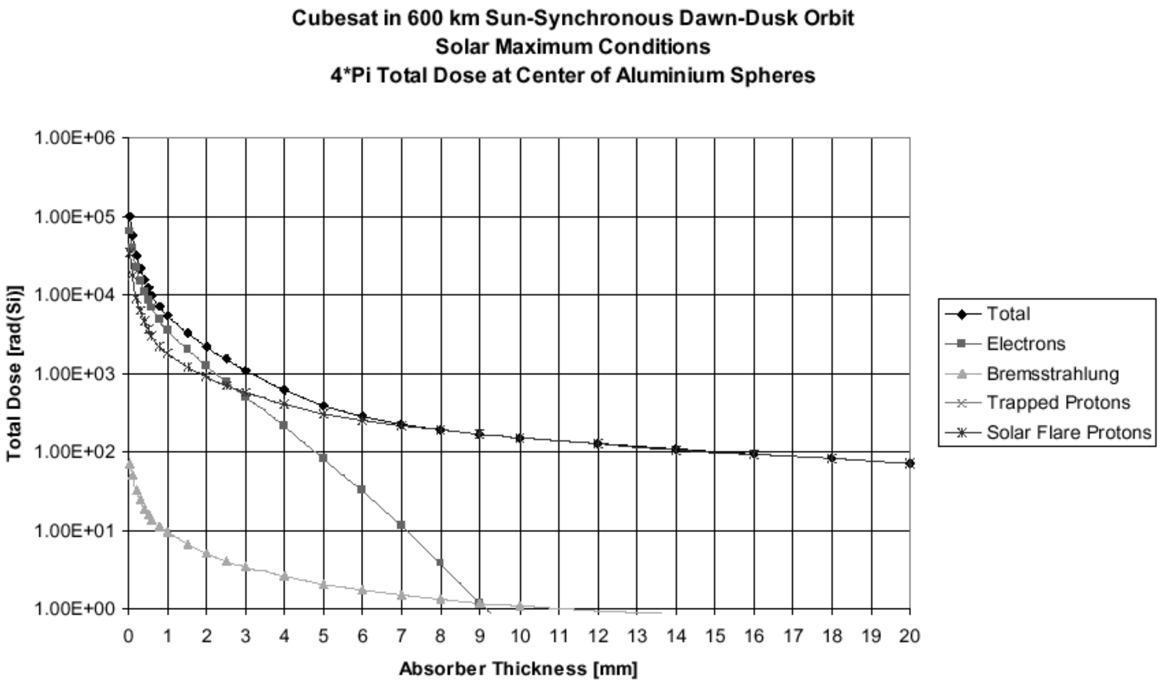

Figure 9 - Ionizing radiation as a function of shield thickness

4π-geometry refers to the fact that the radiation is omnidirectional and can hit the components from all directions – 4π solid angle. This spherical geometry is a reasonable approximation to a small cube, especially as the circuit boards are aligned with the satellite panels. As can be seen, the satellite will receive around 2 krad/year with a 2 mm aluminium shield in the projected orbit.

Electronics is damaged by ionizing radiation in several ways. Some effects are mild and passing, while other destroys the component. Active components are most sensitive, as their function depends on very small structures in semiconductors. The smaller structures are, the easier they are to damage. Passive components are practically not damaged, as their dimensions are far larger than the scale on which radiation damage occurs.

Active electronics can be protected from the effects of radiation. The most efficient way is to ensure that the radiation does not get to the electronics at all. This can be achieved by shielding, either all of the system or by spot shielding the most critical components. The radiation decreases exponentially with mass thickness in its path, meaning that 3 mm of aluminium is roughly as efficient as 1 mm steel, as steel has roughly 3 times the density of aluminium. The ever-present problem in DTUsat is mass, so effective shielding is not easy to do. Another road is to use components that are inherently radiation tolerant. This means components that are built using bipolar transistors instead of CMOS, or components with larger chip area per transistor. These are typically the components of yesteryear – older technology is better suited to cope with space than new, high-performance, low-power CMOS chips. However, to make the satellite function with the available power, we need pretty good performance. An old NMOS 8031 microprocessor draws almost the entire power budget[27] even without the peripheral components that it needs to work, so to go back to that technology is not an option. It is also possible to buy radiation-hardened components, but that is very expensive. The computer group found that a simple 8kb ROM cost 13.000 dkr (about $1500)[28], if it was to be rad-hard and tested. That is a factor of about 500 over normal cost, so that is also not an option. The reason for this huge difference in price is the very low volume and the testing needed to prove that the component is actually near immune to radiation. However, a lot of the components on the market are radiation resistant enough for a mission of a year or two in our orbit. The problem is to find them and test them, but if that is done, one can have the best from two worlds: Good performance and adequate immunity to radiation at a reasonable price.

There are several different ways in which electronics can be disturbed by radiation. We will not go into all possible failure modes, but a few are critical to understand the tests that we will need to do.

Single event upsets, SEU, happens when a quantum of radiation is transformed into a voltage pulse by hitting silicon. This can create a spike on the output of any active circuit, but corrects itself as the charge diffuses away. This is the least critical failure mode, as it is self-correcting and in itself harmless. However, it might have critical influence on the system, if the spike is large enough to have significance for the digital system or if it triggers an unfortunate behavior. E.g., we would be very sorry if the tether released itself 2 days into the mission because of a SEU. SEUs are caused by ionizing radiation releasing electrons into a sensitive structure on the chip, which treats them as a signal. It is thus just as important where the electrons are released as how many they are, that is, how much energy the particle deposited. Electrons induced in the power lines, for example, hardly have any effect, while electrons induced in the gate of a small-geometry transistor are far more critical.

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[27] 175 mA @ 5V = 875 mW with all outputs disconnected. The sustained onboard power is believed to be around 1 W. Data sheet from http://bellota.ele.uva.es/~jesus/datasheets/intel/8051.pdf, page 6.

[28] Sølvhøj et al.: Construction of an On Board Computer for a Student Satellite. Available at the DTUsat homepage.

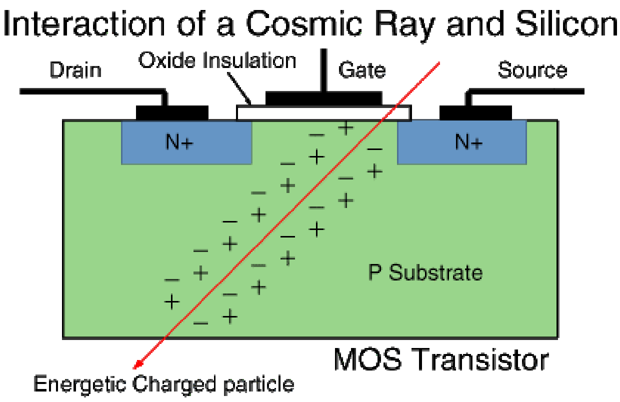

Figure 10 - SEU physical mechanism[29]

SEUs are countered by assuring that a few spurious signals do not affect the operations of the satellite. This can be done in software by debouncing incoming signals, in hardware by using small values of pull-up or pull-down resistors and by wired-and of several redundant signals or time delays in order to activate critical functions.

Single event latch-up, SEL, is a failure mode in which a parasitic thyristor (SCR) in CMOS circuits is brought into conduction. Latch-up does not occur in bipolar, GaAs, ECL, or linear circuits.[30] The SCR is an unfortunate side effect that is difficult to avoid when manufacturing CMOS chips. It consists of two back-to-back bipolar transistors connected to the power rails. As there is no connection to the gate of the SCR, it is normally of no importance. On earth, it can be activated by connecting an input to a voltage greater than the power supply voltage. The current into the protection diodes to the rails will then put a potential on the gate, big enough to switch on the SCR. In space, a SEU can easily happen at the gate of the SCR, as the gate has a very big area and is an easy target. When this happens, the SCR shorts out the power supply. Once started, the SCR keeps itself in conduction and can only be reset by removing the power from the chip. This better happen fast, as the chip will dissipate a lot of power and can burn out in seconds.

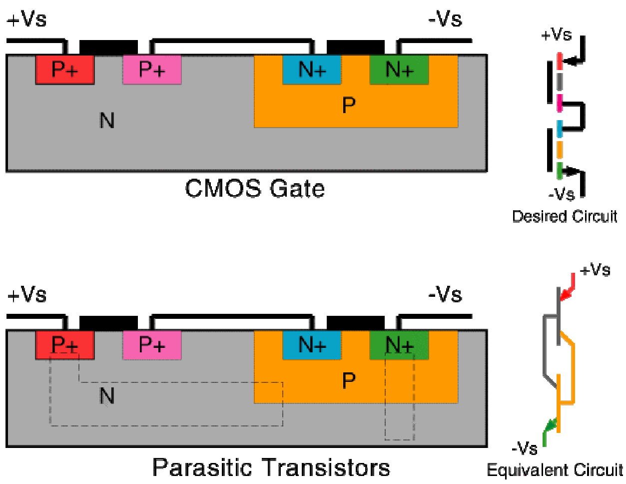

Figure 11 – Placement of the parasitic SCR inside a CMOS circuit

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[29] Illustrations of single event effects from http://www.aero.org/seet/primer
[30] Space Radiation Effects on Electronic Components in Low-Earth Orbit, available from http://www.hq.nasa.gov/office/codeq/relpract/1258jsc.pdf

We will be designing current monitors to ensure that the satellite shuts itself down in the case of a latch-up.

Total ionizing dose, TID, will destroy the chip sooner or later, no matter what we do. Depending on the geometry and technology of the chip, this might happen at anything from about 15 krad for state-of-the-art small geometry to several hundreds of krad for older, bigger geometry or specially treated chips. It is, however, quite difficult to predict the TID tolerance of a given component. As an example, NASA has tested both the Intel 80486DX33 and the Pentium III-700. NASA reports that the original 80486, which is made in 1 µm CHMOS IV technology, gives in at 12-15 krad(Si)[31]. Some chips stops functioning, all goes outside specifications. The Pentium III, made in 0.25 µm technology, withstands at least 100 krad(Si)[32]. Also SEL sensitivity is much lower in the Pentium III than in the '486. The mechanism of TID is that the doping of the material diffuses when the chip accumulates radiation, making the transistors drift in sensitivity and increase their leak currents and increasing both dynamic and static power consumption. At a certain point, a transistor fails to respond to the signal from the previous one, and the chip stops functioning.

We will screen the components we use to ensure that none will stop working within a reasonable operating period.

There are several other failure modes, such as single event burnout, that affects MOSFET power transistors, but most are quite specialized and will not be treated here.

It is nice to know that some manufacturers, e.g. National Semiconductors, have already radiation tested their military products. This means that e.g. Nationals 54FACT-series of logic circuits can be safely used without further testing[33].

Environment Tests

To find out if the designed transceiver will work in space, we have to test it under circumstances seldom experienced by commercial electronics. The electronics must work at extreme temperatures, in vacuum and exposed to ionizing radiation.

To test for the temperature, climate chambers are available in several departments at DTU. It will not be very difficult to test the transceiver for operation at –40 to 85 degrees centigrade, as these temperatures are not that extreme for many other used, e.g. holding microorganisms inactive or curing glues. However, it is seldom the case that a vacuum is needed at the same time. We have not looked into this yet, as we think it more appropriate to get the transceivers working first. Actually, both vacuum and temperature tests really should wait until the engineering model is operative and tested thoroughly at room temperature.

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[31] http://radhome.gsfc.nasa.gov/radhome/papers/intel.htm
[32] http://radhome.gsfc.nasa.gov/radhome/papers/i062100.pdf
[33] http://www.national.com/appinfo/milaero/files/ROM_Logic.pdf

As for the rest of the environment tests, it does not make sense to carry them out before an engineering model including the structure of the satellite has been built. Some tests cannot be carried out at all – or at least very expensively – on the ground, e.g. plasma tests.

To guard our satellite from the effects of the ionizing radiation in space, we will need to design it to recover from the soft errors automatically and test all components for chips for susceptibility to both soft and hard errors. For example, the current strategy is to power down the entire satellite if a latch-up is detected. If this happens often, say once a minute, it will be very annoying. If very central components cause a lot of latch-ups, we will probably spot shield them to save weight.

To find out which components in the system that are radiation sensitive, we have done a total dose test at component level, and we will do a combined latch-up/upset and total dose test at system level when the different boards are built and integrated to an engineering model. The component level total dose test will hopefully rule out very sensitive components before too much work has gone into designing a circuit around them, while very bad results in the latch-up test will require shielding or redesign.

Total Dose Test

The total dose test was done partly in a Cobalt-60 gamma cell, partly in a new facility capable of very low dose rate, both situated at Forskningscenter Risø[34] near Roskilde.

A gamma cell is a small chamber that can be exposed to radiation. The gamma cell on Risø is built on the same principle as the one in this diagram.

[34] Risø National Laboratory is a Danish government-supported research facility specializing in renewable energy sources, material science, optics and agricultural production. Risø also consults the government on nuclear issues and has until recently been running the only Danish nuclear reactors. More information on http://www.risoe.dk

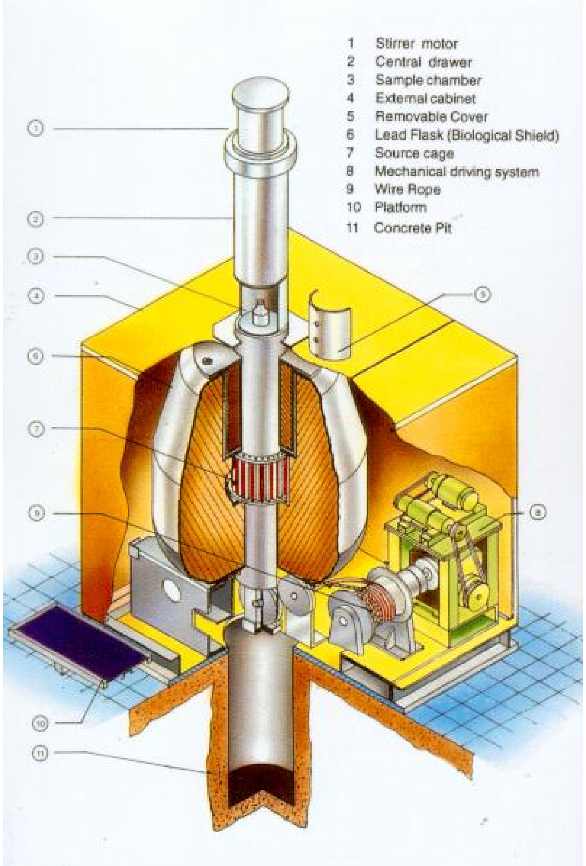

Figure 12 – Schematic drawing of a gamma cell [35]

The irradiation chamber is a section in a lead stick, which can be moved up and down. In the center of a lead shield, a rotating source cage is placed. No matter if the irradiation chamber is retracted or inside the shield, no radiation will leak due to the double shielding. The radiation source is Cobalt-60 placed in rods in the source cage. The cage is rotating during the irradiation in order to make the dose homogenous. In the chamber at Risø, a interface system controlled the exact irradiation time, which was keyed in from a table of dose rates updated once a month as the ^{60}Co decay.

Conversion of Dose to Water to Dose to Silicon

The gamma cells at Risø are calibrated to deliver a specific dose rate to water. Chips, however, are generally made from silicon, so the amount of energy the radiation deposits in the chip itself is different. We would like to thank Uffe Korsbech, associated professor at the Measurements and Instrumentation Systems at Ørsted-DTU, for helping us with these calculations.

In general, to evaluate the accumulated dose in a material due to gamma radiation, one has to calculate the kerma. Kerma is an acronym for "kinetic energy released in material", that is, it will depend on the fluence rate and energy of the gamma photons, the shielding of the volume of interest, the build-up factor for the shielding material, the energy of the photons, the tendency of the material to absorb gamma photons at specific energies and the

[35] Illustration from http://www.barc.ernet.in/webpages/letter/newsletter_year_1999/jan.html

irradiation time. This adds up to a summation over all gamma photon energies of these factors:

$$K = \sum_{E=0}^{\infty} \varphi(E) \cdot E \cdot e^{-\mu_s d} \cdot B(E, \mu_s d) \cdot \frac{\mu(E)}{\rho} \cdot t \quad \left[Gy = \frac{J}{kg} \right]$$

The SI unit for kerma is Grey [J/kg] absorbed dose. The unit used for kerma in this report is rad, a deprecated unit that is often used in the space industry. 1 Grey = 100 rad.

The summation covers all photon energies E, φ(E) is the (differential) fluence rate of photons of energy E hitting the material to be irradiated, exp(-μd) represents the transmission factor through a shielding material, and B(E,μd) is the build-up factor for the same material. μ_s is the absorption coefficient for the shield and d is the thickness. μ/ρ is the energy dependent mass energy absorption coefficient for the specific photon energy, and t is the time. The kerma is equal to the dose if the charged particle equilibrium is ensured, e.g. by surrounding the radiation chamber with a scattering material. In the gamma cell at Risø, steel is used. This attenuates the radiation, but also causes the radiation in the chamber to consist of photons of different energies, from the maximum 1.33 MeV from ^{60}Co down to almost 0, which is a more realistic approximation to the radiation in space.

Regarding shielding, we decided to expose the chips to radiation while they still were packaged in plastic boxes to protect them from static electricity and to avoid excessive handling in order to center the chips in the chamber. The density of the box was found to be very close to 1000 by floating it in water. The thickness was measured to 1.5 mm. The transmission of the primary gamma-rays (1.17 MeV and 1.33 MeV) through 0.15 g/cm^2 mass thickness of polyethylene is 99% - and taking build-up into account an effective transmission of almost 100% is obtained. This also the case for Compton scattered photons except for the very lowermost energies. The assumption is therefore correct, and the plastic cases will have no significance.

Luckily, the chambers we used were already calibrated to a specific and controlled dose to water. Ignoring the influence on the fluence rate from backscattering from the different amount of non-absorbed radiation, which is safe given the very small volume of the chips, the only parameter different for water and silicon is the mass energy absorption coefficient, μ/ρ.

μ/ρ [cm^2/g]	0.5 MeVχ	1.0 MeVχ	1.5 MeVχ
Water	0.03299	0.03100	0.02831
Si	0.02973	0.02776	0.02531
Water/Si	1.1096	1.1167	1.1185

Figure 13 - Mass energy absorption coefficient μ/ρ (cm2/g) for Si and water for different energies

One observes that the ratio is almost constant for the energy range of major interest. In average the doses to water is 1.115 times the dose to silicon. Therefore the doses to water should be divided by 1.115 in order to get the doses to silicon. It can be seen that silicon absorbs about 10% less radiation than water.

We did not know the exact relationship when we exposed the components to radiation, so for a first approximation we used the doses 1, 2, 5, and 10 krad to water. This corresponds to about one half to five years in our orbit when protected by 2 mm aluminium.

The total doses used were:

Batch	Dose rate (H_2O)	Dose rate (Si)	Exposure time	Total dose (H_2O)	Total dose (Si)	Months @ 2mm Al
1 krad	27.93	25.05	35.8	1000	0.897	6
2 krad	27.93	25.05	71.6	2000	1.794	12
5 krad	27.93	25.05	179.0	5000	4.484	30
10 krad	27.93	25.05	358.0	10000	8.967	60
2 krad slow	0.055	0.050	40140	2000	1.794	12
Units	rad/s	rad/s	seconds	rads	rads	Months

Unfortunately, the radiation shield will probably be much thinner than 2 mm. A likely value at this time is more like half a millimeter, which, as seen on Figure 9, will mean a much larger radiation dose rate. We did not know this at the time of radiation, but it would have been more realistic to test for 10, 20, 50 and 100 krad.

Possible errors

One possible error in this test is the high dose rate. In space, as mentioned, the doses used in the test will accumulate over years. This is not very practical for test purposes. We used a dose rate of about 25 rad(Si)/s, corresponding to the American military component burn-in and testing standard MIL-STD-883E-1019.4 Dose rate B[36] (except the subsequent report requirements), which is closer to the real life values than the 50 rad/s Dose rate A-variant, which has been used to space qualify components until about 1992. Now, National Semiconductors and others uses a variant called 1019.5, which unfortunately is more difficult to use, as it requires measurements done for 168 hours after irradiation and in reality measures the shape of an anneal curve for the quiescent current[37].

The old method should be good enough for testing our components, but it introduces some errors. CMOS chips are more sensitive to higher dose rates, but anneals over time if removed from the radiation source. Given lower dose rates, the chips will endure a higher total dose. Bipolar chips are the other way round. They will endure a higher dose at higher dose rates, but will fail at a lower total dose at lower dose rates. As this is not taken into account in our test, we might end up with slightly misleading results.

However, as we still corresponds to the 10 year old standard, we are reasonably sure of usable results – if a chip still works after 10 krad using MIL-STD-883E-1019.4, it will probably work just fine over the service life of DTUsat.

[36] The full standard is available from http://www.dscc.dla.mil/Downloads/MilSpec/Docs/MIL-STD-883/std883_1000.pdf. For some reason, only Method 1019.4 is included, but 1019.5 is used universally in the industry.
[37] For more information, see http://www.national.com/appinfo/milaero/files/ROM_Logic.pdf, page 16.

Results

As we have not yet tested our own prototype boards, we do not know what effect the radiation have had on our components. However, three other hardware groups have tested components from the same batch. The power group found a slight increase in current consumption at 10 krad for CMOS SSI logic circuits, a few percent, but has not yet tested the most critical components – the highly integrated switch mode power supply chips. The attitude control group found a very slightly increased current consumption and an increased offset error in biCMOS operational amplifiers. All components stayed within specifications. The computer group found increased current consumption in the Flash chip, but has not yet tested the CPU.

No groups have yet reported destroyed chips. Given this, and given data found on NASAs radiation test site[38], we would not expect to see any parametric or total failures at all until about double the maximum dose[39]. Had we known this page and the typical values before testing, we would have made a batch with a higher dose to check for possible near-suspect components.

However, some devices might still prove to be susceptible to SEL or SEU. Only bombarding the devices with energetic particles while they are running can test this. We intend to do exactly this when an engineering model is finished.

Latch-up Test

As described, the latch-up test will not be carried out until an engineering model exists. We have, however, done research on how it could be carried out.

Ideally, the test involves an ion accelerator capable of accelerating different ions to different energies. One then records the number of latch-ups as a function of beam intensity[40] while sweeping the ion energy from a few MeV to about 50-80 MeV or until the latch-up frequency stops rising with the particle energy. This procedure produces a curve similar to the one below.

[38] NASA/GSFC Radiation Effects & Analysis Center at http://radhome.gsfc.nasa.gov/top.htm
[39] NASA reports (http://radhome.gsfc.nasa.gov/radhome/papers/intel.htm) that the original 80486, which is made in 1 µm CHMOS IV technology, gives in at 12-15 krad(Si). The Pentium III, made in 0.25 µm technology, withstands at least 100 krad(Si). Also SEL sensitivity is much lower in the Pentium III (http://radhome.gsfc.nasa.gov/radhome/papers/i062100.pdf).
[40] Measured in particles per square centimeter per second

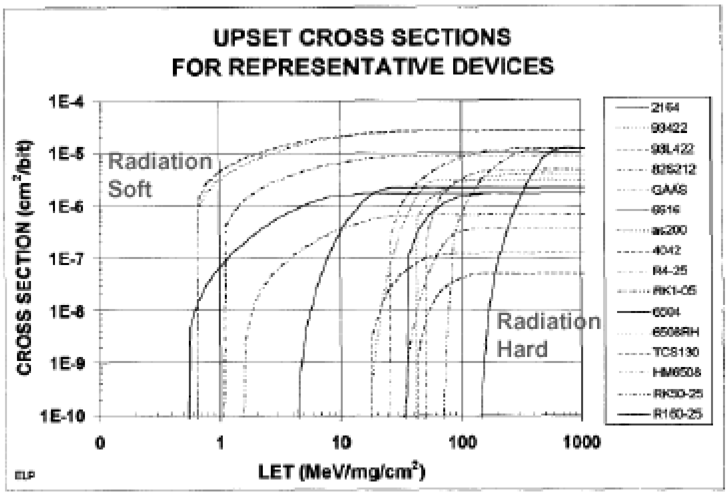

Figure 14 - Number of SEU/SEL (given as cross section) as a function of LET energy

Heavy ion accelerators are not easy to come by in Denmark. However, many big hospitals have cyclotrons to manufacture short-lived radioactive isotopes for use in scintographs, a medical scanner that maps body metabolization or trace mineral distribution by counting the number of decays in different parts of the body. The Danish Rigshospital (National Hospital) uses a 30 MeV proton cyclotron, which it is possible to use for this purpose. The beam current is variable from a few picoampere to half a nanoampere, and the beam diameter about 2 cm. As the beam energy cannot be varied very much, we will not be able to make the full test, but as we know the distribution of particle energies in our orbit, we will be able to test if the LET threshold is above or below 30 MeV, and we will be able to pinpoint the components causing it by recording the beam position (or rather, the position of the XY-table that is moving our setup across the beam) when the latch-up occurs. If the LET threshold is above 37 MeV, the component will not cause problems in low earth orbit[41], so if we see no problems at 30 MeV, the components will probably do just fine.

We do expect both single event upsets and latch-ups at this test. As we are not able to find out where the component latch-up 'knee' is, we will not be able to calculate the frequency of latch-ups and upsets in space, but we will be able to identify the components and systems causing them and taking action, as e.g. spot shielding or, if absolutely critical subsystems as the latch-up protection circuits proves latch-up prone, to redesign systems or replacing chips. Spot shielding involves placing a copper or aluminium layer on both sides of the component – that is, also on the bottom side of the PCB. Redesigning anything will probably delay the entire project, but that is after all better than a satellite 'dead in the water'.

Anyways, this test must be postponed until an engineering model is finished and operational. This is planned to be the case at the beginning of the summer holidays.

[41] http://radhome.gsfc.nasa.gov/radhome/papers/B092500c.pdf

Ground station

The design of the ground station was not originally meant to be a part of this project. However, it quickly became apparent that the preparation of the radio design and the calculation of the link budget depended heavily on the choices of ground station. Therefore the issue was taken under consideration and a preliminary design was prepared. This section will describe the ground station solution as proposed by the radio hardware group. The solution is not final and the exact composition, fine-tuning and precise calculations are meant for the ground station group to complete, with the radio hardware group standing by to aid in any way possible.

Analysis

Since the satellite uses an AMSAT frequency several possibilities arises. As AMSAT has members all around the world, Denmark AMSAT-OZ, a large numbers of people use the satellites already operating in the same frequency band on a daily basis. This means that hardware is widely available and even more important, support and guidance is possible through other AMSAT members. This could prove an invaluable resource in the construction and testing phases of the ground station where solutions/guidance to possible odd behaviour of the equipment could be found.

The ground station composition can be split into different parts: The antenna, the feeding network, radio transceiver, and others. To determine the best composition the different parts are analysed below and a proposed configuration is given.

Antenna considerations

The most important part is of cause the antenna, for which different possibilities are available.

It is preferable to have as high antenna gain as possible and this can be achieved by using a parabolic dish. At the Engineering College of Copenhagen in Ballerup a 25 m parabolic dish is located originally thought as a backup ground station for the Danish satellite Ørsted. The antenna is fully equipped but need certain alternations to operate in the 435-438 MHz band. The possible gain of this antenna is approx 38 dB. To operate the antenna authorised personal must be present at all time, remote control is not an option.

A parabolic dish is (was) also located at the roof of building 348 at DTU, with a diameter of 3 m. The dish has been used for propagation purposes only and lacks a receiving head. It is equipped with a tracking system but has not been in commission for some years. It is however conveniently close and access is easy. The approximate gain achievable is 19 dB.

A third option is to use other Cubesat groups as example and use Yagi-antennas. Due to AMSAT Cross-Yagis for the specific frequency band are available and cheap. They have a relatively high gain approx 16 dB, low wind-factor and only need a feeding network as well as a rotator to function. The Cross-Yagis can be stacked thereby adding another 3 db per doubling of elements. An array can be set-up on the roof of building 348 for easy access especially during installation and testing.

Proposed solution
The option selected is the latter. It can be installed on the roof of EMI building 348 for easy access to the hardware during installation. The roof is specifically designed to support antennas with a ground plane and reinforced concrete plates. To gain an extra 3 dB antenna gain, two X-Yagis mounted in an array is used giving a total of 19 dB. The satellite control room can be placed on the 2nd floor just below the roof to prevent unnecessary cabling and by using conventional AMSAT equipment it will also be possible to draw on the experience of AMSAT people in Denmark and abroad.

The chosen antenna is the 2x19 element 70 cm Cross Yagi from Tonna[42]

Transceiver considerations

A transceiver is needed at the ground station to pickup the received signal from the antenna. Since we are operating in the 70 cm band the choices of transceivers are limited. An obvious choice is the FT-847[43] satellite transceiver from Yaesu. This transceiver accommodates the radio amateur's satellite frequency bands, 144 MHz and 433 MHz and is capable of SSB, CW, AM, FM and digital modes. A search of the Internet shows that this transceiver is widely used among AMSAT people. The transceiver has an output effect of 50 W @ 433 MHz, which should be enough so that we can avoid extra amplifiers. Again due to the wide use of this transceiver among radio amateurs, resources are available on the Internet.

Figure 15 - Yaesu FT-847 Transceiver

Based on its capabilities, which meets our demands, and the fact that the FT-847 is so widely used, it becomes the proposed transceiver for the ground station.

Feeding network considerations

Since the antenna consists of an array of two X-Yagis a feeding network is needed to deliver the signal from the transceiver in a correct manner. The X-Yagis have two active elements on each antenna so the corresponding elements on each antenna must be feed with the exact same signal. At the same time the polarization used is left hand circular,

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[42] See **2x19 x-yagi.pdf** at www.dtusat.dtu.dk for specifications.
[43] For further specifications about the Yaesu FT-847 see www.yaesu.com/amateur/ft847.html

which means that a 90° phase delay must be inserted for the same element on each antenna. During operation of the satellite in orbit it is possible that the satellite at times is faced exactly opposite than intended. To receive any signals in this situation, a polarization switch from left hand to right hand circular polarization must be included in the design.

Proposed solution

To divide the power from the transceiver to the four driven elements, three power splitters are needed. These can either be bought specific for 435 MHz or constructed using coaxial cable.

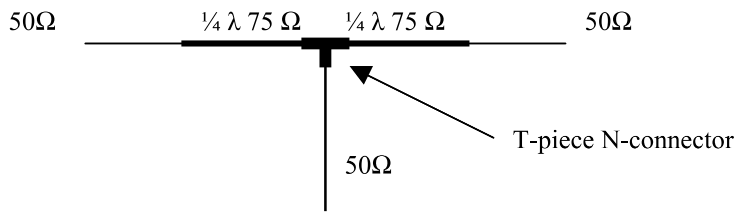

Figure 16 - Construction of a power splitter

By using two ¼ wavelength 75 Ω coaxial cables the two 50 Ω cable ends transforms into a single 50 Ω. The value of 75 Ω is chosen since this is a standard value and is not the optimal configuration. The correct value is sqrt(2) times 50 ohm equalling 70.7 ohms. Further calculations on this are needed, especially on the effects if 75 ohm cable is used.

The polarization switch can be made by a relay that "inserts" an extra 180° of cable if a change in polarization is wanted and the rest of the time it is just shut. The proposed relay is the CX600N 50 Ω relay[44], which is equipped with female N-connectors thereby enabling easy installation.

The same method as above is used to introduce the 90° phase delay. A cable is cut in the exact length equivalent to 90° and inserted into the signal path. The complete proposed solution is seen in the picture below

[44] The CX600N can be obtained from www.dmtonline.dk

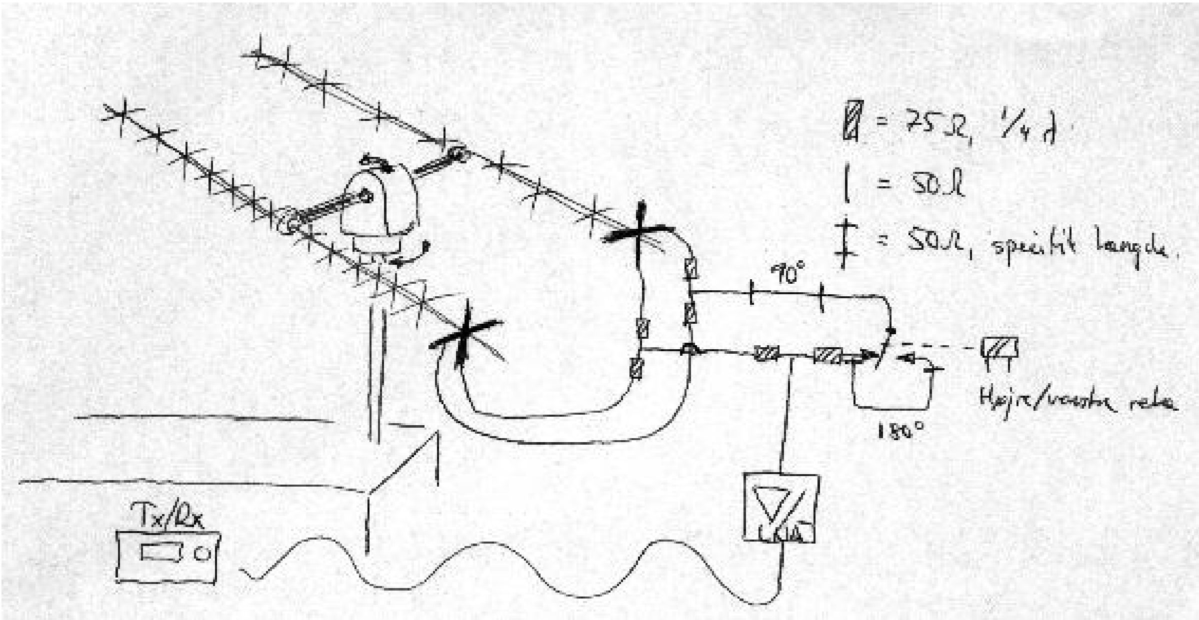

Figure 17 - Total configuration

As seen on the picture a low noise amplifier, LNA, will be needed to amplify the received signal. This must be done as close as possible to the antennas, meaning directly after the last power splitter. The reason for this is to eliminate any noise after the amplifier and at the same amplify the received signal. The proposed LNA is the SP7000[45] with a build-in TxRx switch to bypass it during transmission. The LNA have a small signal gain of 20 dB and a noise figure of 1 dB.

Physical considerations

The two antennas must be pointed towards the satellite at all times, this means that active tracking is needed during the communication window. This can be done using the satellite rotor G-5500B from Yaesu[46], which is capable of a rotation range of 180° elevation and 450° Azimuth, which meets our requirements.

Figure 18 - The G5500B Rotor from Yaesu

[45] The SP7000 can be obtained from www.dmtonline.dk
[46] Further specifications on the rotor can be found at www.yaesu.com/amateur/g5500.html

This will require a second cable to be draw from the rotor control box in the control room to the rotor. The “two” rotors, azimuth and elevation, requires 6 conductors each. As seen on Figure 17 a crossbeam is needed to accommodate both antennas. This also helps to distribute the weight load evenly on the rotor, which is preferred. It is important that the crossbeam is not be made of a conducting material, as this will affect the transmission- and receiving capabilities of the array. The effect of the crossbeam material on the performance of the array must be verified by simulation.

The actual distance between the two antennas on the crossbeam must also be simulated in order to achieve optimal performance, simple calculation based on a equation from the “Radio Amateur’s Satellite Handbook” gives the result of approx. 2.12 λ, but this needs verification.

A third variable that has an effect on the performance of the array is the placement of the array above the ground plane. The physical location of the array is the roof of building 348 at DTU and this roof has been build with antenna placement in mind meaning that it’s equipped with a complete conduction ground plane. However the exact distance from the ground plane to the antennas must be calculated and simulated.
To ensure that the antenna array is firmly secured on the roof at the desired distance from the ground plane a tower structure is needed. As the antennas are “lifted” approx. 15-20 m above the surrounding landscape the wind have unhindered “access” to the antennas, therefore requiring a robust construction. Again with the StenSat group ground station in mind[47], a Glen Martin tower[48] can do the job. These towers come in different dimensions and are designed for AMSAT uses. It is advised to consult the workshop located in building 348 to see if they have other suggestions or recommendations.

The physical location on the roof will be at the opposite end of the access way, the former location of the parabolic dish, in this end a “trapdoor” is located through where the signal cable can be drawn. From here it will be able to follow the ceiling of the 2nd floor to the student room where the operation room will be placed.

Further design considerations

The antennas used are the 2x19 element 70 cm Cross Yagi from Tonna. This antenna has a few “special features” it pays to beware of. First of all it is not very stable or robust, this is primarily because the 3 m antennas consists of two parts which is only held together by a cramp which also doubles as the cramp used to fasten the antenna to the crossbeam. This causes the antenna to bend a little at the middle, which is not desirable. A solution to the problem is to introduce either a wooden stick or an aluminium pipe down the inside of the antenna square pipe, extending an arbitrary length on both sides of the joint. This will require that the closest elements must be taken off and their hulls redrilled. The length of the introduced pipe or stick must be long enough the give the needed support but as the same time not add too much extra weight to the antenna.
The active elements on the antenna are placed approx. 20 cm apart. This means that a delay must in inserted into the cable that feeds the front most element. It pays to beware of this when designing the feeding network for further details see the antenna manual. When

[47] See www.stensat.org/GroundStation/GroundStation.htm
[48] See www.glenmartin.com/catalog/page14.html

connecting the cables to the active elements the housing used on the antenna is faulty. It only enables the cables to enter from below. This placement of the cables causes harms the performance of the antennas as the cable "interrupts" the active area of the antennas. The solution is to cut a hole in the housing parallel to the antenna itself and then lead the cables backward and out. Again see the antenna manual for details.[49]

As the transceiver is located approx. 50 m. of cable away, a low loss cable has been chosen. The Aircom Plus® has a loss of 8.2 dB/100m at 432 MHz[50]. The cable has a diameter of 10.3 mm and it likely to be quite stiff. As a comparison a standard 50 Ohms coaxial cable, e.g. the RG 58 has a loss of 33,2 dB/100m, so there is a lot to be gained by using Aircom Plus.

Figure 19 - Aircom Plus 10,3 mm cable

Where possible all cables, relays, power splitters and so on should be connected using the standard N-connector to ensure both quick and easy installation and to minimize any noise from other types of connectors.

Rotor Control and Modem Considerations

The above analysis is primarily concerned with the physical design of the ground station from the reception of the signal to the delivery at the transceiver. This leaves two important areas still to consider: the rotor control and the modem connection from the transceiver to a computer.

The awareness of the satellite's position in space is taken care of by a controlling ground computer, which runs a special software package. Buying the Yaesu GS-232C rotator controller can make the connection between the software and the rotor control box using a simple RS-232 connection. However this rotor controller costs[51] nearly as much as the rotor itself, which makes a homebrew version an obvious replacement. That is, if manpower can be found for the job, schematics and software code for a rotor controller can be found on the Internet.

The second problem is the data connection between the transceiver and the computer, but as the modulation form is not yet final this aspect cannot be resolved. A modem can be implemented in various ways, either by using the soundcard of the computer, using a commercial off the shelf (COTS) modem, or by making one our selves. But the final solution depends on the choice of modulation.

[49] These special considerations are also discussed in two documents the **jordstation-arbejdsdokument.doc** and **70 cm højre venstre omskifter.doc** found at www.dtusat.dtu.dk
[50] See www.ssbusa.com/aircom.html the cable can be acquired at www.dmtonline.dk
[51] See the budget in the appendices.

Summary

The proposed solution here presented is meant as a reasonable final solution, giving an idea of the major parts involved and how they there are connected to each other. The final composition, fine-tuning and especially the mathematical simulation and optimisation is meant for the newly formed ground station group to complete. The specific hardware proposals are essential to the current configuration and alternations or replacements must be thoroughly analysed before carried out. The radio hardware group will, of course, be standing by to help whenever needed.

Current Status and Future Work Packages

To obtain a clear view of what the current status of the project is and what work still needs to be done a short summery is presented.

As for the radio hardware the first prototypes have been developed and the first PCB for the nRf401 has been build, but not tested. The computer interface board has been build with one functioning as planned and the other needs some error finding before it will work satisfactory. The special components required for the RF2905 has been identified and acquired so that sufficient stock will be available for the remaining prints. The RF2905 PCB is designed, but needs to be constructed and both prototype prints need testing.

To test the transceivers by using the computer interface boards, special test programs need to be written. This should end with the possibility to test the transmission capabilities of the prototypes using a computer to control the data send/received in order to verify the quality of the radio link. All peripheral electronic needs designing, construction and testing with the, hopefully functional, radio prototype prints. This includes the PA, LNA, onboard computer interface logic, PSU, latch-up protection, circulator, automatic beacon and possibly the G3RUH modem. After finishing the test of the separate modules, an integration test should be carried out, and a PCB including all transceiver modules need to be drawn and constructed. Further tests, including environment testing are then needed to confirm the function of the complete pre-flight model.

The frequency application has been submitted and no major workload is expected in that area. However, the modulation issue has not yet been resolved, and we expect to start working on this problem at once.

The different components have been exposed to radiation at Risø and no further radiation tests are planned before a latch-up test of an engineering model consisting of pre-flight or engineering models of all satellite subsystems. The already exposed components need testing to see what effect if any the radiation has had. This cannot be done until the prototype prints works.

A ground station proposal has been made and the work handed over to the ground station group. We are of course standing by to help with any practical construction. The modem issue still needs to be resolved and it is most likely to be a joined effort between the radio hardware and ground station groups.

Conclusion

As stated in the introduction, the focus of this project quickly changed from the actual design of the radio hardware to a much wider focus on the general communication problem. For that reason the main purpose has not been reached.

As for the frequency issue the most interesting band is the 435-438 MHz for which a frequency application has been submitted to the international frequency allocator with recommendations from AMSAT-OZ. Reply have not yet been received.

A link budget for the radio link has been prepared and the results are satisfactory. The downlink should give a Signal-To-Noise ratio of 21 dB and a Received-Signal-Strength of –91 dBm after a Low Noise Amplifier. The proposed ground station transceiver has a sensibility down to –120 dBm, which is sufficient. The uplink shows a Signal-To-Noise ratio of 36 dB and a Received-Signal-Strength of -82 dBm after a Low Noise Amplifier. The two satellite chipset candidates have a sensibility down to approx. –100 dBm that should be adequate. The Signal-To-Noise ratio should give a Bit-Error-Rate large enough, by far, to make error-correcting codes pointless.

The interface between the radio hardware and the other groups has been designed, documented and will be implemented into the later designs.

A selection process has zeroed in on two possible chipsets, the nRF401 and RF2905, for which preliminary designs and PCB layouts have been done. The prototype PCB print for the nRF401 is finished but not tested. To test the functionality of the prototype prints a computer interface board has been designed and constructed. A selection process has also been carried out for the power amplifiers and the RF2155, with an output effect of 500mW, has been chosen. An overview of the peripheral electronic needed for tending to the chipset needs and extra functionality has been established, but no exact design has been carried out.

The effect of the ionizing radiation in space on the components has been uncovered and a total dose test has been carried out on the major components. The total dose results are still to come but the effect are expected to be minor based on the results from the other groups and on literature studies. Latch-up test for the engineering model is postponed until the engineering model actually exists. We expect that to happen sometime this summer.

A complete ground station solution has been proposed based heavily on ideas from other Cubesat groups. The proposed and naturally placement of the antennas is the roof of building 348, housing electromagnetic systems, and 2nd floor would ideal for the operation room. Transceiver is proposed on the basis on availability and functionality, as with the rotor. The modem issue is still unresolved until the modulation has been firmly established. The actual construction and optimization of the ground station has been handed over to a new group starting this semester.

The workload is still great, but as the project is also very exciting, the workers struggles on with a, hopefully, more focused point of view.

Lyngby, February 2002

Anders Nielsen, c973535	Heine Bodekær, c973808	Niels Holmgård Andersen, c973399

Appendices

Budget

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Tentativt budget for Radio Hardware pr. 04/12 2001

Priser i parantes er ikke indregnet i totaler.
Der er ikke regnet med nogen form for nedslag i listepriser.
Alle priser er excl. moms og fragt.

Komponenter til transceiver
---------------------------
nRF401                                     0 dkr        nVLSI, har doneret komponenter og
evaluation-boards mod at få strålingstestresultater
RF2905 + diverse aktive komponenter     1432 dkr        RF Micro Devices, har givet 1000 stk-priser
Passive komponenter, krystaller, print  1500 dkr        Diverse leverandører
Opbygning af ekstra flightmodel etc.    1000 dkr        Diverse leverandører

Strålingstest (dækker også Computer, Power og Attitudekontrol)
Total dosis med gammastråler               0 dkr        RISØ - kontakt: arne.miller@risoe.dk
(Latch-up test                          9000 dkr)       Rigshospitalet
                                       ---------
Radio hardware i alt ca.                4000 dkr
                                       =========

Det kan være en god ide at lave en total strålingstest af en engineering model på Rigshospitalet når vi
kommer så langt.


Jordstation
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Transceiver - Yaesu FT-847             12796 dkr        www.betafon.dk, ordrenr. A11790010
Strømforsyning til transceiver          1000 dkr        Overslag - 13.8V, 20A - evt. selvbyg ud fra
AT-computerstrømforsyning
Modem/TNC - PacComm Spirit 2            2250 dkr        http://www.paccomm.com/spirit.html - bruger
G3RUH-modem. Ellers lydkort i kraftig pc.
Rotator - Yaesu G-5500B incl. styring   4556 dkr        www.betafon.dk, ordrenr. A12900003
Rotatorcontroller - Yaesu GS-232C       3036 dkr        www.betafon.dk, ordrenr. A04580001 - virker
meget dyrt! - selvbyg oplagt.
Antenner - 2 stk F9FT 2x19 X-yagi        896 dkr        www.edr.dk, varenummer 20438
Antennebeslag, mast etc.                2000 dkr        Overslag
LNA - SP7000 med indbygget TxRx switch  1440 dkr        http://www.dmtonline.dk 0.9 dB noise, 20 dB
gain - eller selvbyg. Masser af hjælp at få, incl færdige konstuktioner.

Alle kabler og konnektorer fra www.dmtonline.dk
Kabel - 8 leders kontrolkabel - 40 m     240 dkr        Kabellængder baseret på montering på taget
af EMI - 20 m fra jordstationen
Kabel - 50 ohm AirCom+ coax - ca. 35 m   539 dkr        -8dB/100m
Kabel - RG11/U 75 ohm coax - ca. 3 m      15 dkr        -18dB/100m - evt. leveret fra IKT
1 T stykke til N-konnektorer - hunhanhun  58 dkr        Montering på relæ
3 T-stykker til N-konnektorer - hunhunhun 174 dkr       Montering på LNA samt samlestykke til
antennekablet
Han 10.6 mm N-konnektorer - 16 stk       912 dkr        Balance ikke fastlagt endnu
Hun 10.6 mm N-konnektorer - 4 stk        120 dkr
Coaxrelæ CX600N                          500 dkr

(Computer - Duron-klasse                4000 dkr)       Er ikke medregnet i budgettet.

Reserve                                 3000 dkr        Der er betydelige usikkerheder på disse
beløb, især da fragten ikke er inkluderet.
                                       ---------
Jordstation i alt ca.                  32500 dkr
                                       =========
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Pin budget

Weight budget

Schematic for nRF401

PCB layout for nRF401

Schematic for RF2905

PCB layout for RF2905

Schematic for Computer Interface

PCB layout for Computer Interface

Frequency Application (submitted November 25th 2001)

IARU/AMSAT Frequency Coordinator
C/O Ib Christoffersen, OZ1MY, AMSAT-OZ

Technical University of Denmark, November 23rd 2001

Dear Sir,

We hereby apply for a frequency in the 70-centimeter radio amateur satellite band for a new satellite, DTUsat. DTUsat is a CubeSat[52] built by engineering students at the Technical University of Denmark as an educational project. We are currently a team of 40 persons working on the satellite, which we hope to launch in the spring of 2003. The orbit is currently unknown, but will probably be near-polar with an altitude of 650 km.

The satellite will be equipped with three payloads. A CMOS camera for ground and launch separation photography, an electromagnetic active three-axis attitude control system, and an electrodynamic tether that will be used for changing the orbit.[53]

However, a satellite without communication might as well be made of concrete. We are currently designing a half-duplex digital transceiver for the satellite, but for this to be really useful, we will need an operating frequency, too.

Our reason for applying for a radio amateur frequency is threefold.

- As we are students and on a budget, the availability and pricing of radio amateur ground station equipment is a big advantage.
- As the satellite is a small project without high-profile payloads, the difficulty of international frequency coordination would make it next to impossible to get a global frequency assigned.
- As this satellite is the first we build, we would appreciate amateur assistance in acquisition, tracking, and telemetry recovery.

We realize that the frequency bands that AMSAT holds are valuable assets.

- Our satellite uses half-duplex communication, meaning that a single 9k6 FSK frequency slot in the 70-cm band will suffice. The bandwidth needed is thus small.
- Our satellite is designed to commit suicide by dropping itself into the atmosphere in about 2 years. This is accomplished by means of an electrodynamic tether, which will be the first of its kind. The time span of the mission is thus limited.
- Our satellite will incorporate a further suicide command, which will stop the transceiver on a ground command if need should arise.
- Our satellite will provide the radio amateur satellite community with some service when it is not communicating with the command station.

As the satellite is very small, the power and space available is very limited. It is thus not feasible to fly a transponder – linear or digital – and comply with the communication part

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[52] The Cubesat concept was proposed by Prof. Robert J. Twiggs of Stanford University in 1998. Details are found at http://ssdl.stanford.edu/cubesat/

[53] More details on the project are available at the DTUsat homepage, http://www.dtusat.dtu.dk. The page is currently used for working on the project, but it will be refitted for external reference before December 2001.

of the IARU Operational Guidelines[54]. We instead propose to comply with the technical investigations part by flying a test transmitter. The satellite will broadcast a CW callsign and AX.25 packets containing telemetry in 9600 bps FSK format. Our idea is to repeat the telemetry packets, but step down the radiated power from the transceiver maximum of about 500 mW to almost nothing to facilitate test of ground equipment sensitivity. This suite of packages will be repeated about once a minute, starting with full power and stepping down. Each packet will contain telemetry on the power level used. We will provide certificates for amateurs successfully receiving and forwarding telemetry, stating the power level received.

As the on-board power is very limited, we will have to ask the community not to operate the satellite. This unfortunately limits the usefulness of the payload data downlink to the satellite amateurs situated in Northern Europe, who might be listening when we operate the satellite from Denmark. The payload data will be made publicly available via the Internet. The test transmitter will be available worldwide and provide general telemetry to interested parties.

We are currently designing for 9600 bps FSK, which will fit the 25 kHz spacing in the current frequency allocation, Doppler shift not included. Any frequency band in the 70-cm satellite band will be fine, e.g. the available frequency at 435.200 MHz or the hole at 436.325 to 436.475 MHz. We will of course comply with your guidelines regarding spurious emissions.

We are looking forward to hear from you.

Best regards,

Anders Nielsen   Heine Bodekær   Niels Holmgård Andersen
DTUsat/radio hardware

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[54] http://www.iaru.org/satellite/prospective.html - Section VI.A