

Additional technical information for CanSat competition 2014

Information for users of the European CanSat kit
prototype 2013

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Table of contents

| | |
|--|----|
| Introduction | 5 |
| Defining missions | 6 |
| Budget constraints..... | 7 |
| Presentation and reports..... | 8 |
| Presentation..... | 8 |
| Reports | 8 |
| Introduction to measurement tools..... | 9 |
| Length..... | 9 |
| Ruler..... | 9 |
| Caliper | 10 |
| Angles | 11 |
| Protractor..... | 11 |
| T-square..... | 12 |
| Mass..... | 13 |
| Scale..... | 13 |
| Electronics: voltage, current, resistance..... | 14 |
| Multimeter | 15 |
| Example of CanSat setup with the European CanSat kit | 16 |
| Parachute design and construction | 18 |
| The physics behind the drag parachute..... | 19 |
| Shapes of drag parachute | 21 |
| Lifting parachute..... | 23 |
| Testing your parachute | 24 |
| Introduction to electrical circuits..... | 25 |
| Reading of a circuit..... | 25 |
| Components..... | 26 |
| Sensors | 29 |
| Communication..... | 33 |

| | |
|---|----|
| Batteries and power system..... | 34 |
| Battery types..... | 34 |
| Advantages and disadvantages..... | 35 |
| Calculations with a battery..... | 35 |
| Battery tips and tricks | 36 |
| Introduction to soldering and circuit assembly..... | 38 |
| Soldering..... | 39 |
| Radio communication..... | 42 |
| Introduction to programming | 45 |
| Data inconsistencies..... | 46 |
| Introduction to data analysis..... | 47 |
| From data to measurements: calibration..... | 47 |
| Results presentation..... | 49 |
| Other resources and further information..... | 53 |

Introduction

This document was written as a technical add on for the CanSat kit user manual for the STEM center in York. Since the STEM center works in 2013/2014 with the European CanSat kit prototype, it lacked some technical information necessary for completing a CanSat competition.

This document is divided into a project management section, a mechanical section and an electronics section. The chapters are written for students and teachers in mind and try to teach technical background as well as hands-on skills vital for completing a successful CanSat project.

Defining missions

The definition of a mission is very important, because it will determine the complete CanSat project. A mission statement is a statement that will give your project focus. It should be clear and concise. When trying to write a good mission statement, make sure to do a couple of iterations.

Any mission will start with a “why”-question. Why are you interested in A or B? It could well be that what you want to do is not the best method to do it. What we like to see is a mission and a number of options to fulfill the mission. The reasons why your design was the best option should be made clear. For the primary mission, the reason why pressure and temperature are measured is because we can determine the altitude from that. So the primary mission would be to determine the altitude of the CanSat with the use of the temperature and pressure sensor. If the last part was not demanded by the organization other methods of determining the altitude of the CanSat would be good as well. But the team must explain why they made certain decisions.

An example of a mission statement that is not so strong: “Our team wants to make video recordings of the CanSat descent”. This is not a good mission statement, because the “why”-part is missing. An improvement would be “The CanSat will determine the number of animals in a 4 km² area centered on the launch site”.

In a nutshell, the mission statement is an answer to the question “what does our CanSat team want to achieve and why?” Now perhaps it is easy to think of all kind of things that one can do with a CanSat but the “and why?” part of the question is fundamental.

Budget constraints

Every project has limited resources. Examples of resources are production capacity, financial, volume and lots of others. In this chapter the use of a budget to manage the limited resources is discussed. The goal of a budget is to have an overview of the status of the resources so that the project does not overrun the requirements and other constraints.

Any budget starts with a topic, the most obvious is financial. Then the requirements determine the amount that can be used. This can be a constraint, like the cost of the CanSat, but also an estimate of the resource that needs to be made available. Now, it needs to be shown that the project fulfills the requirements. This is done by means of a budget table, an example of which is given in Table 1.

Table 1: an example of a simplified budget

| | Expected [In leafs] | Actual [1/1/2001] |
|---------------|---------------------|-------------------|
| Income | | |
| School | 10 | 10 |
| Sponsors | 5 | 2 |
| Total | 15 | 12 |
| Expenses | | |
| Electronics | 6 | 9 |
| Travel | 6 | 6 |
| Total | 12 | 15 |
| Result | 3 | -3 |

From this budget table, it can be seen clearly that the sponsor income is less than expected and the expenses are more than expected, resulting in a shortage. This is a serious problem. If you would have such a situation with mass or volume the CanSat would not be allowed to fly. So it is very important to keep track of all resources. In the project a number of requirements have/will be given. One of these requirements is with respect to the amount of resources that can be spent on the CanSat. A budget table is a great tool to be informed about the status of the expenditures and income. Any budget table will have three parts an estimation, realization and closing. They will be discussed in short.

The first thing is to determine the budget: what resources are available to spend. In the CanSat case, this can be limited both by what is available from the school or sponsors and what is allowed within the rules. Then an estimation of the expected expenditures must be made. Start with a group brainstorm about what is needed and then try to make a good estimation about the cost. Also allow for some margin, because there will be setbacks. Now you have a great idea with an awesome CanSat but you need to have it finished in time. Work on a time budget; estimate what you need, estimate the time you can spend and again some margin, as you might have setbacks. In general it is better to have a modest CanSat done with a high quality of work compared to a complex CanSat almost ready and with low quality work. Also important is planning, a team member can have time but he might not be able to work because a sensor is not yet delivered.

Hint: generally we overestimate our own abilities. With a budget you can recognize this and possibly fix it.

Presentation and reports.

In order to communicate in a large project, it is essential to have good presentation skills and a good, concise and clear reporting style. Both presentations and reporting are needed for your CanSat project. A small report is needed to relay all project-information to the judges of the CanSat competition. Furthermore, a small presentation is needed to accompany this report and to give more digested information to people who did not read your report.

Presentation

To give a presentation for a lot of people is something that everybody dislikes in the beginning. Some people really find it scary in the beginning, but it is a skill which everybody can learn very quickly. Try to practice a couple of times for a full classroom. Don't learn your presentation "by heart", because it could be the case that you are going to talk faster and faster when you do the final version in public. Some small tips for presenting:

- Try to be as relaxed and normal as possible. This is not some Shakespeare play, it is a technical presentation.
- Speak slowly, don't try to rush everything to the end. If you have a watch or a small clock, take it with you on the stage. You will directly see how much time you have left for your presentation. You can either slow down or accelerate if the time demands it.
- Know your stuff. If you did the research, you will be the person who knows everything there is to know. For questions about the subject you are the best person to answer it. If you don't know the answer then you can always say that it is a good question and you will look for an answer and contact the person after the presentation.
- Have fun. After a while you are not as scared anymore for speaking in public. Try to enjoy it, people in the audience will notice it and find it much easier to listen to it.

Reports

For writing reports the ESA CanSat project has some nice self-explaining report templates. Try to follow these templates by filling in the required information. In reporting it is always difficult to give enough information without overloading people with too much information. Try to put details like electronic schematics in an appendix. The document itself (without the appendices) should be a readable document for a technically educated person.

Introduction to measurement tools

During the production of your CanSat, you will very likely need to measure certain quantities: the diameter of your parachute, the mass of your CanSat, or maybe its battery voltage. To do this, you will need the proper tools. Most of them, such as the ruler or the scale, you are probably familiar with. Other tools, such as the caliper, may be new to you. This chapter will describe some of the tools that you will most likely want to use. Also, the correct usage of them is explained. The chapter is divided into four sections, in each of which a certain measurable quantity, such as length or mass, is treated.

Length

The first and probably most important *quantity* that is measured is the size of objects. This can be the height of a CanSat, or the diameter of a thread for example. The *quantity* we are measuring in these cases is *length*, defined as the distance between two known points. Length can be defined in many *units*. These units are roughly defined in two systems: the *imperial system* and the *metric system*. The imperial system is the most common system used in the US and the UK. The metric system is mainly used in Europe. The units in which a length is most conveniently expressed depends on the actual size that is measured. The height of the CanSat is probably expressed in millimeters (mm), centimeters (cm) or inches (in), and the distance from your house to your school is most likely expressed in kilometers (km) or miles (mi). For the translation between one unit to the other, linear translation rules are defined. These express how many of one unit add up to another unit. For example, 100 centimeters make one meter, and 1000 meters make one kilometer. The other way around also works: one centimeter is 1/100th of a meter, which is 1/1000th of a kilometer. In a formula, this can be expressed as:

$$(0.1) \quad \text{Length}[\text{m}] = 1000 \times \text{Length}[\text{km}]$$

Also the conversion from imperial to metric system is done via linear relations:

$$(0.2) \quad \begin{aligned} \text{Length}[\text{mm}] &= 25.4 \times \text{Length}[\text{in}] \\ \text{Length}[\text{mi}] &= 1.609 \times \text{Length}[\text{km}] \end{aligned}$$

Most of the conversion factors from one unit to the other can be found on the internet or in your science book.

Many tools exist to measure length. The type of tool used depends mainly on the size of the measured object and its shape.

Ruler

The ruler is the length measuring tool that everybody knows. It consists of a straight piece of material, with a series of tick marks at equal distance from each other, which forms the scale of the ruler. It is used for measuring linear lengths, or lengths of objects with a straight edge. Typical dimensions range from 10 cm to one meter. Measuring with a ruler is easy: the first tick mark, typically the zero-mark, is kept next to the first measurement point and the value of the tick mark at the second measurement point is read from the scale. The *accuracy* of the ruler is a figure that expresses the measurement error that is made with it. This figure depends on the spacing of the tick marks. If the spacing is for example 1 mm, and one reads a value of 59 mm between the measurement points, it means that the distance between the points may be anywhere between 58.5 and 59.5 mm. This means that the accuracy of the measurement is plus or minus 0.5 mm. This is usually expressed as:

(0.3) $L = 59 \pm 0.5 [\text{mm}]$

Caliper

A special type of ruler is the caliper. This device is equipped with a “beak” with two “jaws”. One of the jaws is fixed to a ruler, while the other can slide along the ruler. It is therefore an ideal instrument to measure the size of rectangular and round objects. The object is put in between the jaws, the beak is closed around the object and then the measured value can be read. Usually, the jaws are made such that the caliper can measure inner size and outer size of objects, as indicated by (1) and (2) in Figure 1. Also, a depth gauge is usually present, so that the for example the depth of a groove or a hole can be measured. The way this is done is displayed at (3) in Figure 1.

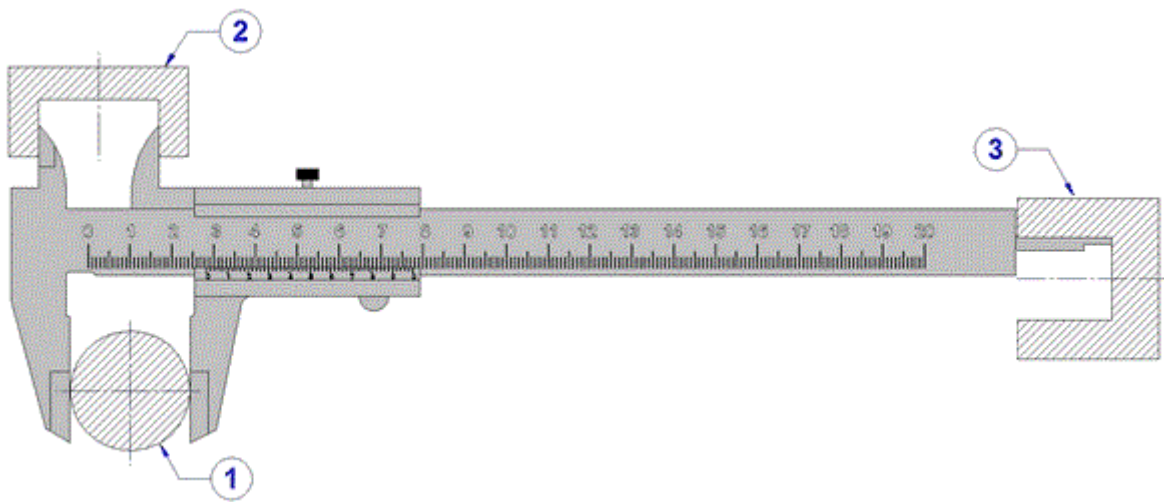


Figure 1: different measurement methods with the caliper (source: craftsmanspace.com)

The accuracy of measurements made with the caliper depends again on the spacing of the tick marks. However, usually the caliper is equipped with two scales: a fine one and a coarse one. Normally, the coarse scale has a 1 mm spacing between the marks, and the fine one has a spacing of 0.9 mm. Such caliper is called a Vernier caliper. The scale is read at the point where the coarse and fine scale tick marks coincide, as indicated in Figure 2. In this way, measurements with $\pm 0.05 \text{ mm}$ accuracy can be made.

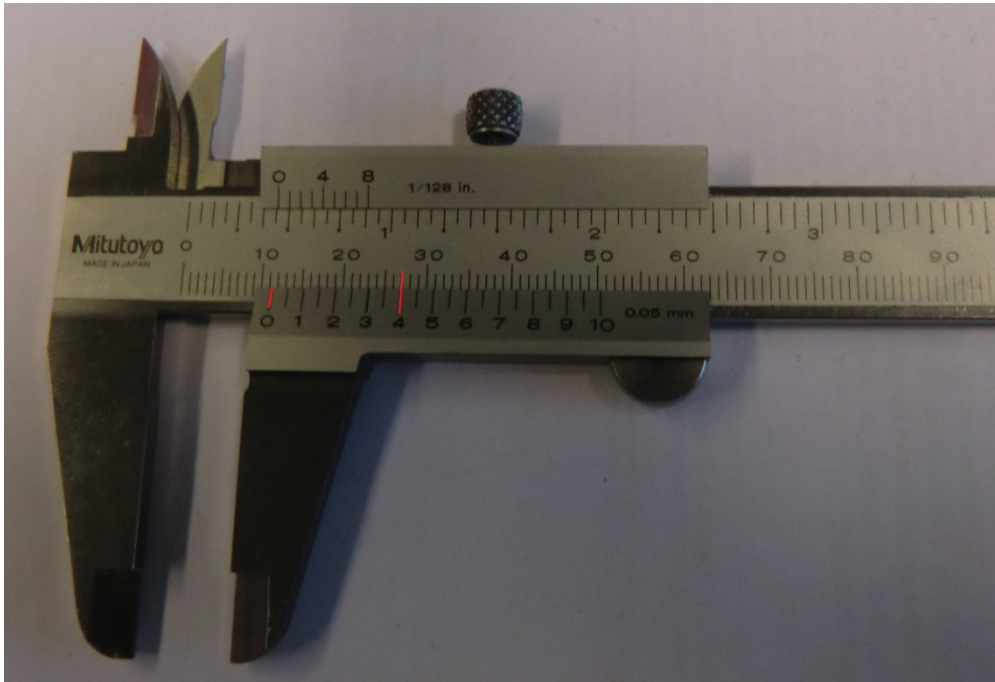


Figure 2: Vernier caliper indicating a length of 11.4 mm (courtesy of T-Minus)

Angles

A second quantity that is important in defining the geometry of objects is the *angle*. The angle between two lines defines the orientation of one line with respect to the other. Angles can be expressed in two types of units: degrees (deg or $^{\circ}$) and radians (rad). The translation from degrees to radians and back is done via expression 1.4.

$$(0.4) \quad \text{Angle}[\text{deg}] = \frac{180}{\pi} \times \text{Angle}[\text{rad}]$$

Protractor

The most widely used tool to measure angles is called the protractor. A picture of such device is displayed in Figure 3. It consists of a scale in the shape of a half circle, with tick marks at equal distances along the rim. The angle of a certain corner is measured by aligning the straight edge of the half circle with its first side, with the center mark of the circle (usually the zero mark) at the corner itself. The angle is then measured by determining which tick mark is coinciding with the second side. The accuracy of the protractor depends on the spacing of the tick marks, just as for the ruler. If the tick marks are spaced with 1 degree angles, the measurement has an accuracy of ± 0.5 deg.

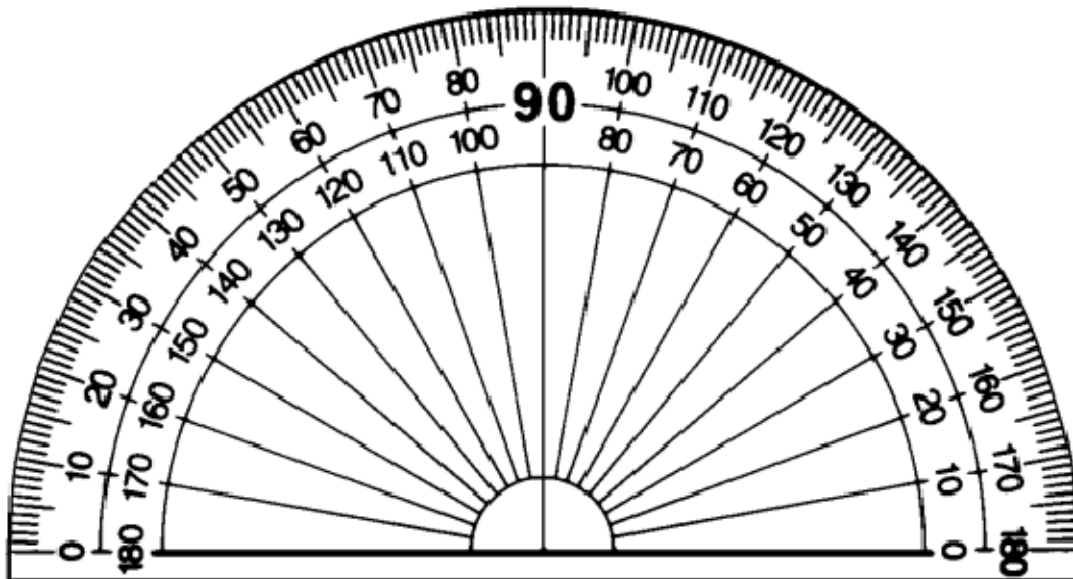


Figure 3: schematic representation of a protractor (source: math8geometry.wikispaces.com)

T-square

A tool that is frequently used to draw corners with a defined angle is the T-square. This device is composed of two parts: the block and the ruler. The angle between the ruler and the block may be fixed at any angle between 0 and 90 deg. For drawing the corner, the ruler is fixed at the desired angle and the block is placed in alignment with the first side of the corner. The base of the ruler is positioned at the place where the corner is to be drawn. The corner can then be drawn by following the edge of the ruler with a drawing tool, for example a pencil.

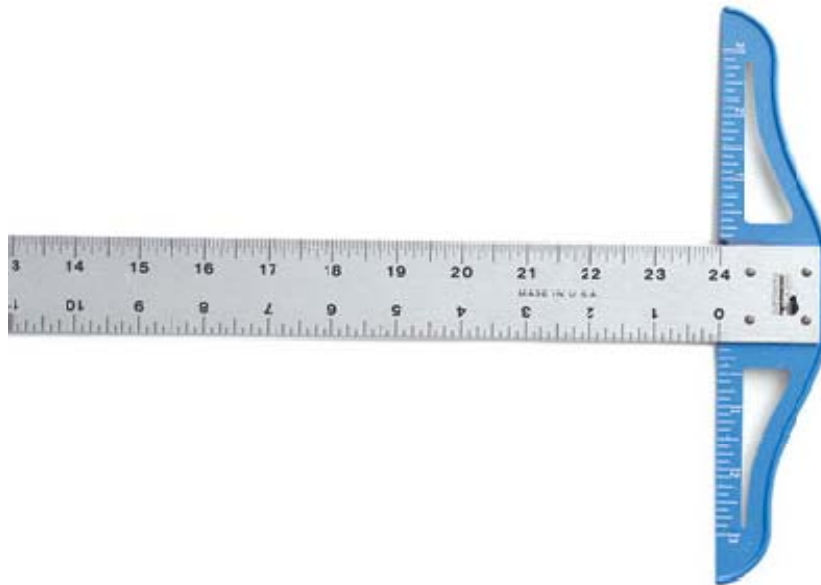


Figure 4: A T-square (source: mathsteward.com)

Mass

The quantities that define the shape and size of an object are now discussed. However, there is one more property of the CanSat that is important to know: its *mass*. Determining the mass of the CanSat is necessary in order to size the parachute, and to verify if the design meets the requirements. Just like the quantity length, the mass can be expressed in metric and imperial units. Metric units are for example the kilogram (kg) or the gram (g), while the mass in imperial units is normally expressed in pounds (lb). The conversion from kilogram to pounds is done by:

$$(0.5) \quad \text{Mass [kg]} = 2.205 \times \text{Mass [lb]}$$

Scale

The mass of an object is normally measured with a scale. A simple scale consists of a suspension hook, connected to a calibrated spring and a pointer. When an object is placed on the hook, the spring will extend with a length proportional to the mass of the object:

$$(0.6) \quad \Delta L_{\text{spring}} = n \cdot M$$

Multimeter

An easy device to measure the electronic quantities is the multimeter. It consists of an electronic measurement unit and two measurement probes. A selection knob is used to choose which quantity is measured, and in which *range*. Measuring the properties at a certain electronic component is quite easy, but it has to be done in the proper way. The voltage over a component is measured by placing the multimeter in parallel with it, indicated by (1) in Figure 5. When the selection knob is set to “voltage”, the display will show the potential difference between the two measurement probes.

Current is measured by placing the multimeter in series with the conductor, as indicated by (2) in Figure 5. In this setup, the flow of electrons through both the conductor and the multimeter will be equal.

Therefore, when the selection knob is set to “current”, the display will show the amperes flowing through the conductor. Finally, the resistance of a conductor can be measured. To do this, it is required that the measured object is isolated from the rest of the electronic circuit, in order to avoid interference of the other electronic components. The multimeter is now placed in parallel with the object and the selection knob is set to “resistance”, as indicated by (3) in Figure 5. It now puts a well-defined voltage over the probes and the object, and measures the current that flows. With Ohm’s law, the resistance of the object can now be determined.

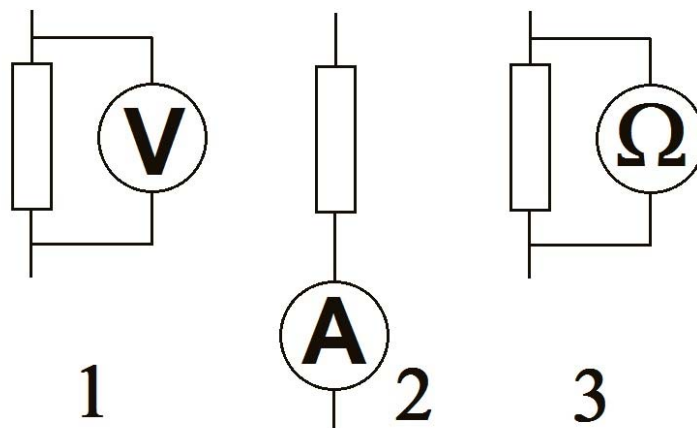


Figure 5: schematics of a multimeter

Example of CanSat setup with the European CanSat kit

There are of course numerous ways to construct your CanSat. The construction is limited by certain constraints set by the organization (such as mass and size/volume constraints). But apart from those, the engineering is only limited by your imagination and your building capabilities. Try to make a baseline which is efficient, but still all parts are easily accessible. This way you have a fair amount of available space in your CanSat for your secondary mission, but still you can easily switch part on site in case of emergency.

Some examples of how you could arrange your CanSat, with the European CanSat kit prototype 2013, are displayed below. Of course you are totally free to choose any arrangement you would prefer.

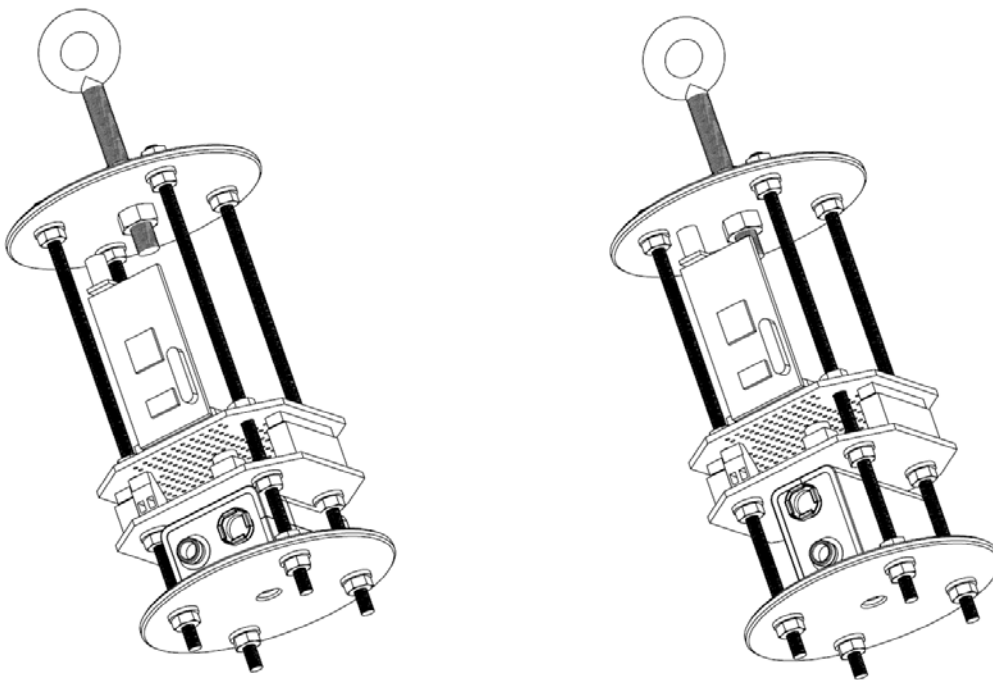


Figure 6: Depending on your desired volume under the MCU board, you can store your 9V battery there

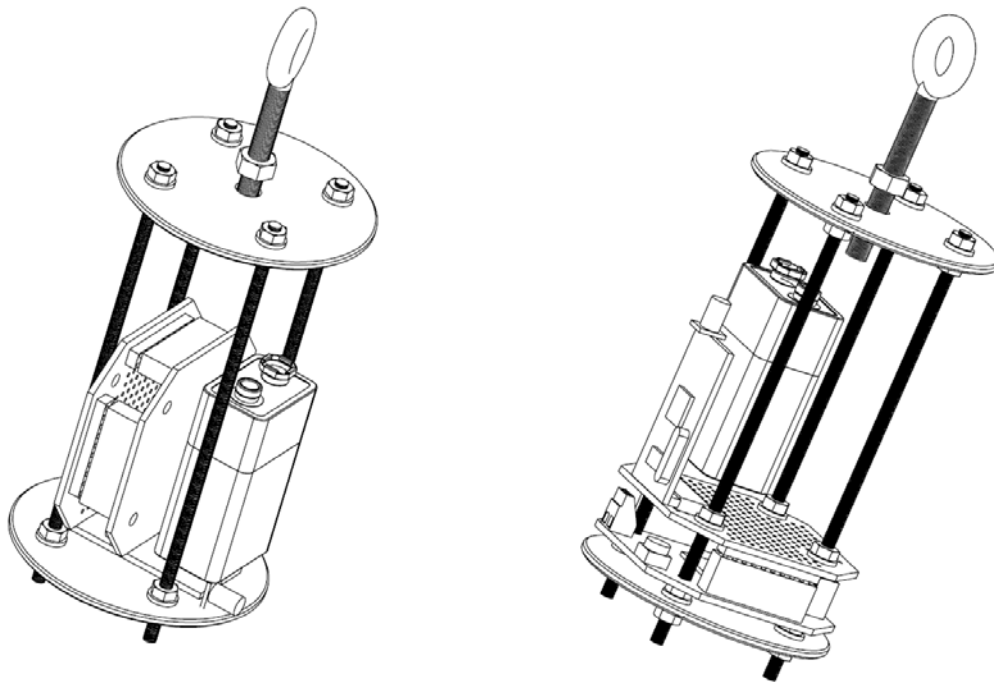


Figure 7: alternative ways to arrange your MCU and sensor board and transmitter

Parachute design and construction

In order to slow down your CanSat, you will need some sort of device that helps it to land. This can be done in numerous ways, but two types of recovery mechanisms are highlighted in this chapter:

- A drag device
- A lift device

The drag device is by far the simplest way of slowing the CanSat down: it creates drag in order to reduce the speed of a falling object. The most commonly known drag device is a parachute. A parachute is a piece of fabric and cables, which create enough aerodynamic drag to slow the object down to a lower descent velocity



Figure 8: a simple parachute, as used to slow humans down from a drop (source USMC)

A lift device is much more complex than a drag device. It is basically a system which creates lift by moving through the air. The air moves over and under the cleverly shaped lifting surface, resulting in a large lifting force and a small drag force. A good example of a lift device would be an aircraft wing or ram air parachute. The big advantage of this type of parachute is that it is potentially steerable, when trimmed correctly. The disadvantage is that they are highly complex to build, difficult to trim and are less reliable in deploying correctly in the air.



Figure 9: a ram-air parachute, as modern parachutists use (source USMC)

The physics behind the drag parachute

The physics behind the drag parachute and the lift parachute are similar in nature. The formula's connected to the drag parachute are:

$$F_{drag} = 1/2 \rho V^2 C_d S$$

Where:

- F_{drag} is the drag force from the parachute [N]
- ρ is the density of air [kg/m³]
- V is the airspeed of the parachute [m/s]
- C_d is the drag coefficient [-]
- S is the surface area of the parachute [m²]

The c_d , or *drag coefficient*, is a dimensionless number which depends on the shape of an object. Basically it is a number that indicates how "easy" air, or any other fluid, is flowing around a shape. If the object is very aerodynamic, like for instance an airplane or a car, this number is fairly low (for example 0.2). If the shape is not so aerodynamic, such as a simple plate or a parachute shape, the C_d will be very high, for example (0.8 or higher).

Of course these numbers are empirical and based on a certain area where this drag coefficient is calculated over.

For a normal circular parachute the drag coefficient will be in the range of 0.75 over the flat surface of a parachute. The flat surface of a parachute is the surface area when you put a parachute flat on a table top.

The density of dry air can be calculated using the Ideal gas law

$$\rho = \frac{P}{R_{specific} \cdot T}$$

Where:

- ρ is the air density [kg/m³]
- p is absolute pressure [Pa]
- $R_{specific}$ is the specific gas constant for dry air
The specific gas constant for normal dry air is 287.058 [J/(kg·K)]
- T is absolute temperature at that altitude. [K]

Under normal circumstances the air density at sea level (15°C) is approximately 1.225 kg/m³.

The temperature at altitude depends of course on the weather and the ground temperature. As a general rule it can be stated that in the troposphere, the lower layer of the atmosphere, the air temperature decreases with approximately 6.5 K per kilometer.

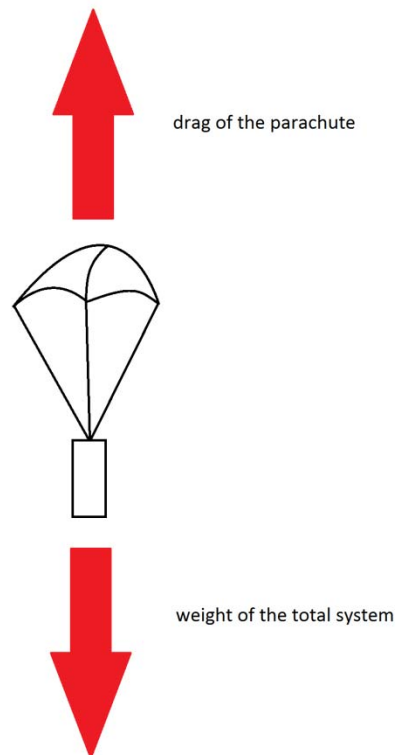


Figure 10: constant descent velocity: an equilibrium between forces (courtesy of T-Minus)

In case of constant descent velocity it can be stated that the weight of the drop mass (or CanSat in this case) + parachute is equal to the drag force of the parachute. This means that the following is true:

$$mg = \frac{1}{2} \rho V^2 c_d S$$

Where:

- m is the mass of the total system [kg]
- g is the gravitational acceleration of 9.80665 m/s² [m/s²]
- ρ is the air density [kg/m³]
- V is the airspeed of the parachute [m/s]
- c_d is the drag coefficient [-]
- S is the surface area of the parachute [m²]

By combining these formulas, we can calculate how big the parachute should be in order to have the desired descent time. Furthermore, by dimensioning the parachute, you can also predict the impact velocity of your CanSat, by taking the air density ρ as the value of ISA sea-level of 1.225 kg/m³.

Shapes of drag parachute

The drag parachute can have all kinds of shapes and sizes. The size of the parachute is a direct result of your drop-mass (the CanSat in this case) and your desired descent velocity.

As with everything in engineering, the shape of your parachute will be the result of all kinds of requirements, for example:

- High drag coefficient
- Packing efficiency
- Manufacturability
- Deployment velocity (airspeed when opened)
- Deployment speed (time from packed to fully opened)
- Deployment stability
- Pendulum stability during flight

There are many different kind of shapes to choose from, many specially designed for different requirements. A good source is the book: Recovery System Design from Th. Knacke, ISBN-13: 978-0915516858.

The normal shape that everybody recognises as a parachute is called the hemispherical design, which has a high drag coefficient (meaning it is very efficient), a fair packing efficiency, but is difficult to produce, since it involves a lot of sewing.

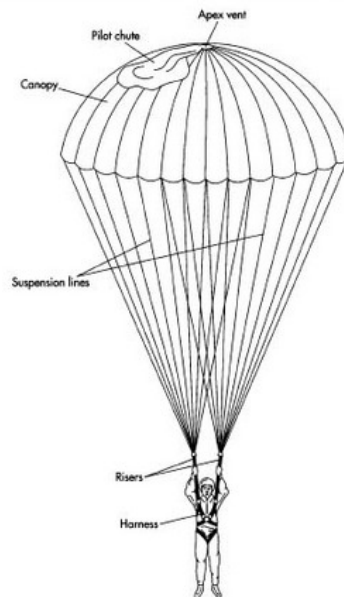


Figure 11: a traditional hemispherical parachute design (source www.madehow.com).

The most used parachute for CanSats and sounding rockets is the cross-shaped parachute (sometimes referred to as cross formed-, X form- or crucifix-parachute) due to its ease in manufacturing and good pendulum stability. A good example can be seen in Figure 12.



Figure 12: A cross shaped parachute(source, www.nakka-rocketry.net)

Lifting parachute

A lifting parachute is a much more complex device than a normal drag parachute. The device is basically the same as an airplane wing but instead of being a rigid structure, it is inflated into its correct shape by the incoming air. The wing will generate lift by the air which is flowing around it. A small added problem with this lift is that it will come at a small price, namely drag.

A lot of formulas that describe the behavior of a lifting parachute go way further than the scope of this CanSat project and go deep into aerospace engineering. The most important factor is the ratio between lift and drag. This ratio, which is for simple lifting ram-air parachutes around 3 to 5, is also known as the glide ratio. Basically this corresponds with the amount of horizontal distance that can be obtained per vertical distance.

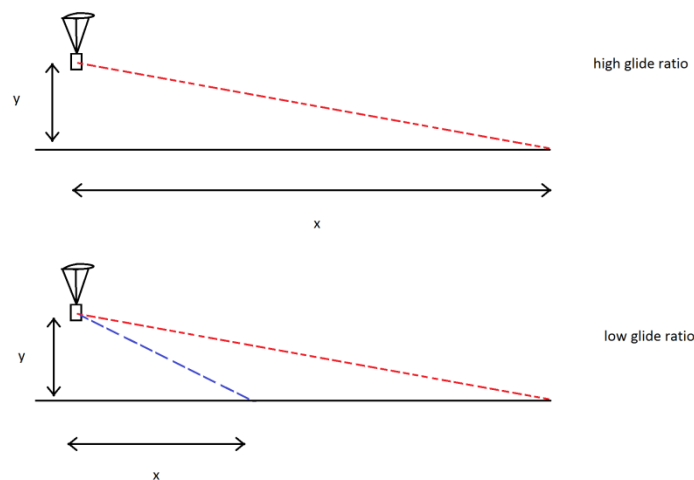


Figure 13: the difference between a high glide ratio and a low glide ratio (courtesy of T-Minus)

In order to steer with a lifting parachute, some steering-lines can be attached to the leading edge of each side of the wing. When one of these lines is pulled inwards, the wing has more drag on that side than on the other side of the wing. This difference in drag can be used to steer the wing into the proper direction.

If the parachute is not properly trimmed, the wing can stall. This means that the wing will stop flying, because the air is not smoothly flowing around the wing anymore. Try to trim the wing forward again in order to reduce this stall tendency.

It must be noted again that this type of parachute is definitely not recommended for beginners and is very difficult to produce, deploy and fly.

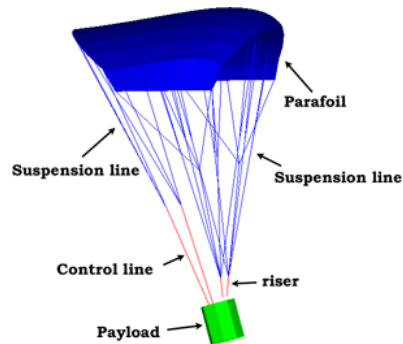


Figure 14: a cansat with a ram air lifting parachute (source Miyazaki Laboratory)

Testing your parachute

A parachute is very easy to test. You can go to a high building where you have permission to drop something small from (with such permission for instance your school building). Measure the drop height in meters before you start. It is good to have a person with a video-camera standby to film all your tests for later analysis. First throw your CanSat in a horizontal fashion to check if the deployment of the parachute is according to your desires. Then throw your CanSat under an angle upwards, so that the descent velocity is stable when it goes through the thrower's horizontal. If you look later on the movie of your test, you will be able to determine the time that the parachute spent descending from that point until it touches the ground. Simple calculation can prove then what the average descent speed in meters/second is. Try to do these kinds of simple tests a couple of times and average your results for best accuracy.

Introduction to electrical circuits

To build the CanSat, you as a team will need to make a small electrical circuit. The system used for the primary CanSat mission is provided, but it needs to be put together. There are many possible secondary missions of which most require additional electrical circuits. This chapter will provide a short description of electrical circuits and the basics of designing and building them.

An electrical circuit is a network of electrical components, designed to fulfill a specific task. There are many different sorts of electrical circuits, like your computer or a telephone. More simple circuits are for example the light above the dinner table or a flash light. The flash light circuit contains three components: a battery, a switch and a light bulb.

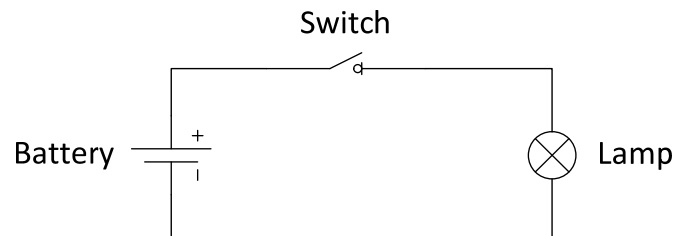


Figure 15: schematic diagram of a flash light

Figure 15 shows a schematic representation of the flash light circuit. In a schematic circuit diagram the components are represented by symbols. Many different components have a dedicated symbol but there are also components that do not. The meaning of the symbols depends on the system used. There are two widely used systems: the American and the European. The reason symbols are used in circuit diagrams is to make it more readable. Search on the internet for “*Electrical circuit symbols*” to find more. The components are connected to each other by electrical wires. In an electrical circuit the wires are normally not called components but connections. In the above picture they are represented by the lines connecting the components. These lines indicate an electrical connection with very low resistance. In most systems copper wire is used for the connection but other options are possible as well.

Reading of a circuit

In properly drawn schematics, there are three methods to make the circuit readable.

The first is reading from left to right. This means inputs are placed on the left side of the circuit and outputs on the right. In the flash light circuit, the battery is the input and the light bulb is the output.

The second method is working from top to bottom. For electrical schematics this means high voltages are on the top of the diagram and low voltages are on the bottom. The positive supply of the battery is drawn at the top and indicated by the longer line and the plus sign.

The last method is the method to draw the connections.

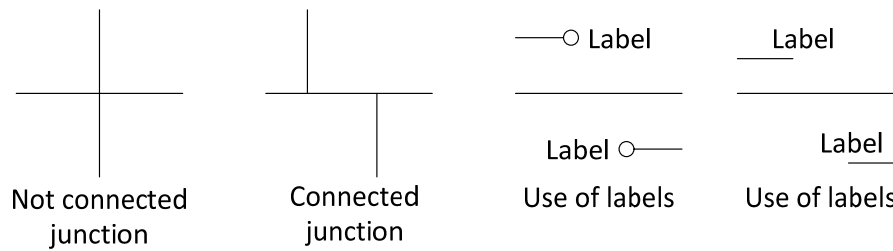


Figure 16: schematic diagram of connected and not connected wires. The labelled wires are connected

In the simple schematic of the flash light there are only 3 connections in only one loop. The simplicity of this circuit makes it very clear. In more complicated circuits there are many more connections. Figure 16 shows how to draw connected and unconnected crossings. The two lines are connected when they are drawn with an offset, and not connected when they cross. The power lines in an electrical circuit are normally connected to many components. To prevent the situation where the drawing is unreadable because it would contain too many lines, simple labels are used. As shown in the Figure 17, all connections with 3V are connected together. The same holds for the 0V connections. However, for the flash light circuit, using only labels does not make the schematic more readable. Finding a balance between labels and lines is dependent on many aspects and to the choice of the designer.

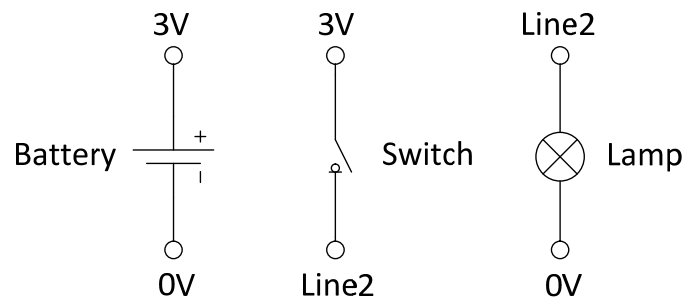


Figure 17: different schematic representation of the flash light. Using labels does not necessarily makes the diagram more readable.

Components

There are many different electronic components available. The core of every CanSat is built up with a few basic components. These components are:

- A micro controller
- A power supply
- A transmitter
- some sensors

In this manual, the T-Minus CanSat kit is used as reference. The same principles apply to other components.

The micro controller is the main controlling and calculating component of the CanSat. There are many manufacturers of micro controllers, which all make almost infinitely many different versions. All of these controllers are based on a sequential processor, surrounded by several hardware interfaces. These interfaces include systems like memory, analogue-to-digital converters and digital communication systems.

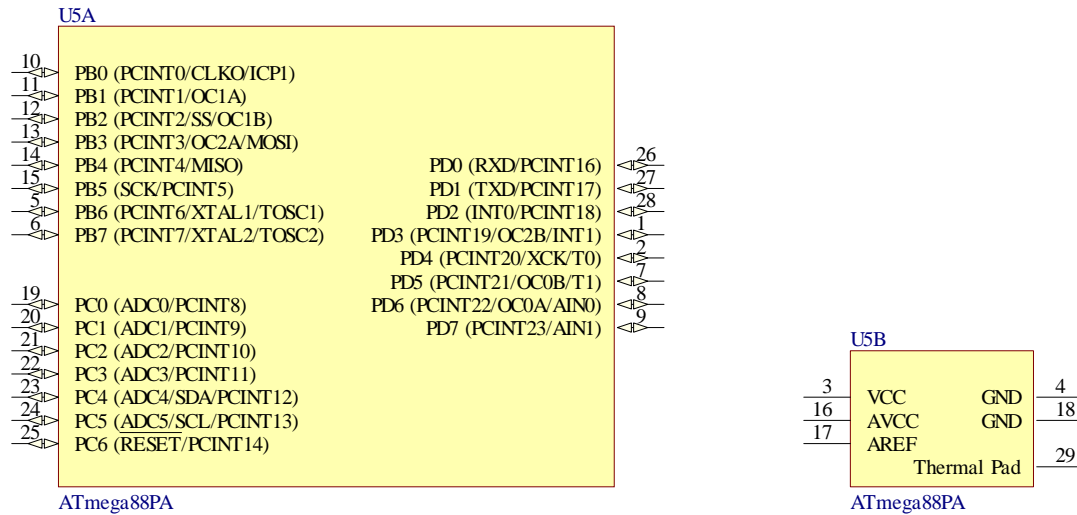


Figure 18 Schematic view of the ATmega88PA micro controller. The schematic is divided into an input/output part (U5A) and a power supply part (U5B).

As the micro controller is a part that has many connections, sometimes up to 144 pins, discussing all connections will not be part of this document. For the Atmel micro controller of Figure 18, there are 3 different types of inputs that will be discussed.

The first type of connection is the “general input/output” or GPIO. In the Atmel micro controller all input/output pins can be used in this manner. Connections starting with PB, PC, or PD are GPIO pins. A GPIO pin can be used as input, where it will read a logical 0 or 1, depending on the voltage that is applied to it. The GPIO can also be set as output where the software determines if the pin is held high or low. If the pin is held high then it will supply the same voltage as is being supplied at the VCC pin(s). When the GPIO pin is held low it will drain current to make supply 0V.

The second type of connection is the analogue-to-digital converter (ADC). Many micro controllers have ADC’s on-board. These can be used to measure a voltage between 0V and the supply voltage. The precision of the measurement depends on the amount of bits the ADC provides. Most ADC’s are 10 bit. A 10 bit ADC divides the voltage range in $2^{10} = 1024$ different steps, where 0 is the minimum value and 1023 is the maximum value. The ADC inputs of the micro controller can be recognised by the labels ADC0 to ADC5, for the micro controller of Figure 18

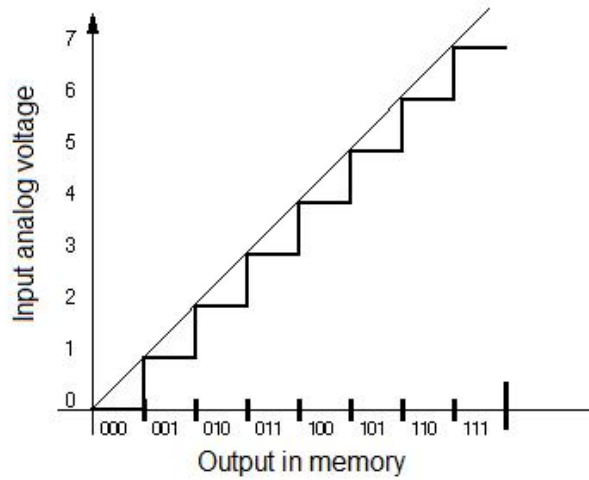


Figure 19 Basic principle of an ADC (source: wiki.ulcape.org)

The last connection that will be discussed in this document is the UART connection. UART stands for Universal Asynchronous Receiver/Transmitter. A UART connection is a basic serial communication system, used by many devices. The com port of a computer uses the same protocol, only with different voltages.

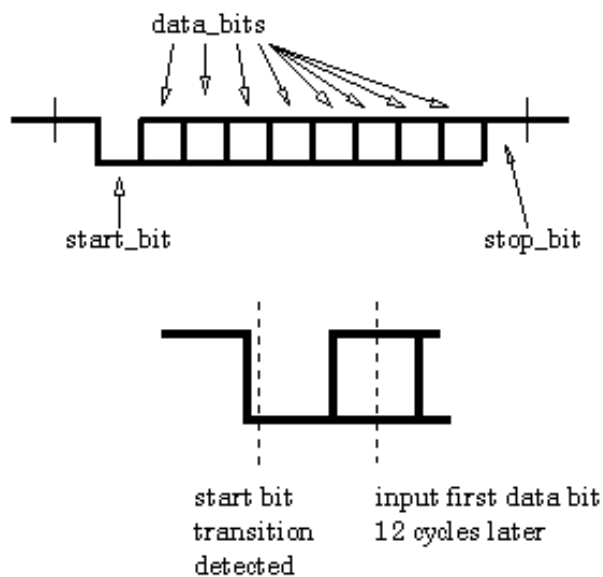


Figure 20 basics of UART communication

For a UART connection, the output of one device is connected to the input of a different device. In Figure 20 the basic protocol is shown. The connection is held high by the transmitter before the communication starts. The transmitter starts the communication by making the line low for a predetermined time. This is done to tell the receiver that data will be transmitted. After this start bit, one or several data bits are

transmitted. At the end of the transmission a stop bit is sent to make the line high again. Normally, 8 bits or 1 byte is transmitted between a start and stop signal.

Sensors

The most basic sensors usually have an analogue output. An analogue sensor provides an analogue voltage, depending on the measured quantity. For a pressure sensor, the air pressure is converted to voltage. As an example, the MPX4115A pressure sensor will be used.

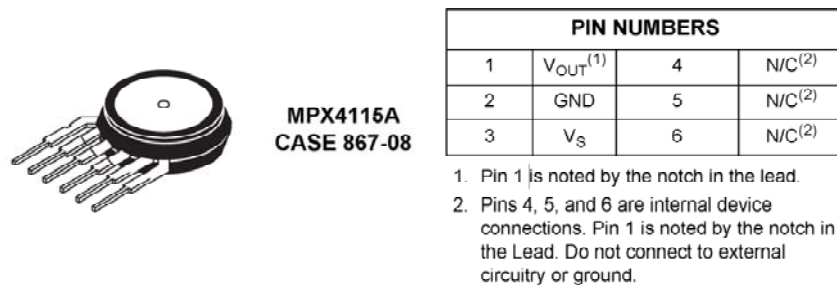


Figure 21: part of the datasheet from the MPX4115 pressure sensor (source Motorola)

The MPX4115A pressure sensor has 6 electrical contacts. The datasheet of the sensor describes the function of each pin. As seen in Figure 21, pin 1 is V_{out} , pin 2 is GND, pin 3 is V_s , the other pins are N/C or “not connect” pins. For this component there is no predefined symbol, which means we have to make one ourselves. Since there are only 3 connections used, the symbol will only contain 3 pins. V_{out} , or output voltage, is an output, so it is placed on the right side of the symbol. GND is ground or negative power supply and is placed at the bottom of the symbol. V_s , or supply voltage, is the positive power supply and will be placed at the top.

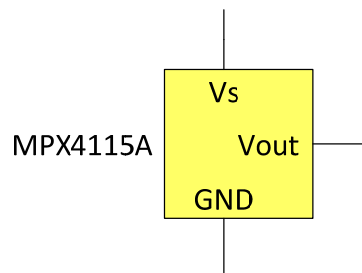


Figure 22: self-made symbol for the MPX4115

To connect the pressure sensor it is important to understand some of its characteristics. The datasheet of a component describes the operational characteristics. These describe properties like sensitivity, accuracy, maximum and minimum operating voltages and current usage.

Table 2: characteristics sheet from the MPX4115 datasheet

Operating Characteristics

($V_S = 5.1 V_{dc}$, $T_A = 25^\circ C$ unless otherwise noted, $P_1 > P_2$ Decoupling circuit shown in Figure 3 required to meet electrical specifications.)

| Characteristic | Symbol | Min | Typ | Max | Unit |
|--|--------|-------|-------|-------|--------|
| Pressure Range(1) | Pop | 15 | - | 115 | kPa |
| Supply Voltage(2) | Vs | 4.85 | 5.1 | 5.35 | Vdc |
| Supply Current | Io | - | 7 | 10 | mAdc |
| Minimum Pressure Offset(3) (0 to 85°C) @ VS = 5.1 Volts | Voff | 0.135 | 0.204 | 0.273 | Vdc |
| Full Scale Output(4) (0 to 85°C) @ VS = 5.1 Volts | Vfso | 4.725 | 4.794 | 4.863 | Vdc |
| Full Scale Span(5) (0 to 85°C) @ VS = 5.1 Volts | Vfss | - | 4.59 | - | Vdc |
| Accuracy(6) (0 to 85°C) | - | - | - | ± 1.5 | %Vfss |
| Sensitivity | V/P | - | 46 | - | mV/kPa |
| Response Time(7) | tR | - | 1.0 | - | ms |
| Output Source Current at Full Scale Output | Io+ | - | 0.1 | - | mAdc |
| Warm-Up Time(8) | - | - | 20 | - | mSec |
| Offset Stability(9) | - | - | ± 0.5 | - | %Vfss |

1. 1.0kPa (kiloPascal) equals 0.145 psi.
2. Device is ratiometric within this specified excitation range.
3. Offset (Voff) is defined as the output voltage at the minimum rated pressure.
4. Full Scale Output (VFSO) is defined as the output voltage at the maximum or full rated pressure.
5. Full Scale Span (VFSS) is defined as the algebraic difference between the output voltage at full rated pressure and the output voltage at the minimum rated pressure.
6. Accuracy (error budget) consists of the following: Linearity, Temperature Hysteresis, Pressure Hysteresis, TcSpan, TcOffset, Variation from Nominal
7. Response Time is defined as the time for the incremental change in the output to go from 10% to 90% of its final value when subjected to a specified step change in pressure.
8. Warm-up is defined as the time required for the product to meet the specified output voltage after the Pressure has been stabilized.
9. Offset stability is the product's output deviation when subjected to 1000 hours of Pulsed Pressure, Temperature Cycling with Bias Test.

Starting at the top of the Table 2, the pressure range is the range of pressures the device can measure. The supply voltage indicates the voltage required on the Vs pin in reference to the GND pin to use the sensor. The board provided with the CanSat kit has a 5V power supply, which is within the range indicated in the table. The supply current of this device is normally 7 mA with a maximum at 10 mA. This current can be used in calculations on required power supply or the expected battery life. The next lines describe how the V_{out} pin reacts to the applied pressure. This part will be required during calibration and analysis of the signal. For this part it is important to note that the output is an analogue voltage.

Connecting the pressure sensor to a micro controller can be done in many different ways. Two things are important in connecting this sensor: the power supply and the fact that the output is analogue. With the output of the sensor being analogue it needs to be connected to an ADC of the micro controller.

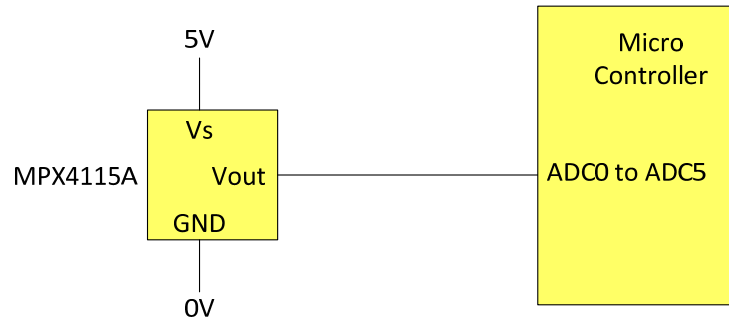


Figure 23: schematic diagram of a connected pressure sensor

Figure 23 shows how this component is connected. The output of the sensor is connected to an ADC input of the micro controller. The V_s and GND pins are connected to 5V and 0V the power supply used in this example.

As example for a temperature sensor, a thermistor is used. A thermistor is a temperature dependent resistor. To measure the temperature with a thermistor there are 2 basic possibilities: on can either put a voltage across the thermistor and measure the current, or send a current trough the thermistor and measure the voltage.

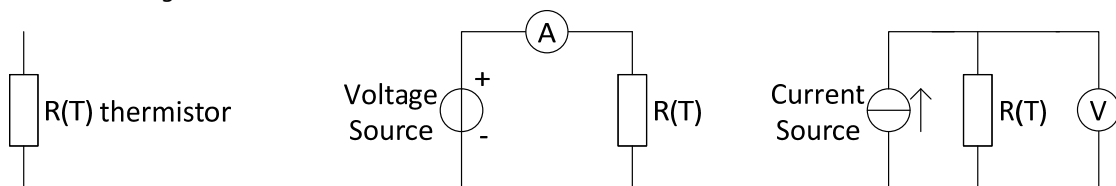


Figure 24: thermistor symbol and the measurement options.

The methods shown in Figure 24 either need a current source or current measurement. The simplest current measurement is the use of a resistor with a fixed and predefined resistance, to convert current in voltage. The drawback of this approach is that the calculation of the temperature becomes more difficult.

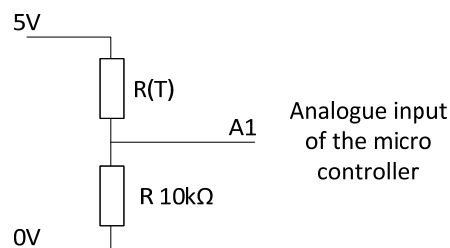


Figure 25: readout of the thermistor

Together with the resistor, the thermistor can be connected like the pressure sensor, in order to read the output voltage.

$$V_{measured} = \frac{V_{source} \cdot R}{R_{(T)} + R}$$

$$R_{(T)} = \frac{V_{source} \cdot R}{V_{measured}} - R = \frac{5 \cdot 10k}{V_{measured}} - 10k$$

The above formula describes the relation between measured voltage and the resistance of the thermistor. With this resistance the temperature can be calculated from the thermistor datasheet. The NTCLE203E3103GB0 thermistor made by VISHAY BC Components is used to describe the basics of the temperature measurement. This is a negative temperature coefficient thermistor, which means that the resistance decreases with increasing temperature.

Table 3: part of the table describing the relation between temperature and resistance from the thermistors datasheet

| Temperature | resistance |
|-------------|------------|
| °C | kΩ |
| 0 | 32.56 |
| 5 | 25.34 |
| 10 | 19.87 |
| 15 | 15.70 |
| 20 | 12.49 |
| 25 | 10.00 |
| 30 | 8.059 |
| 35 | 6.535 |
| 40 | 5.330 |

The datasheet of the thermistor shows a table of the relation between temperature and resistance, of which Table 3 is a part. Using this relation the acquired resistance can be calculated back in to temperature.

Communication

The last part of an electric circuit that will be discussed is digital communication. There are two main options for communication: serial or parallel. In this document, only serial communication will be addressed. The serial communication method used by the CanSat kit as it is provided, is UART. With this communication method there is a dedicated line connecting the transmitter of one device with the receiver of the other. If two-way communication is required, two lines are needed.

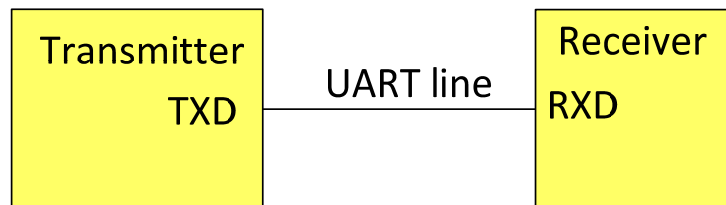


Figure 26: schematic diagram of a UART connection

The UART line is made high and low by the transmitter, depending on whether a digital 0 or 1 is transmitted. To receive this signal the receiver needs to read the line at the right moment to determine whether a 0 or 1 is transmitted. The moment at which the status of the data line is read, is predetermined by the speed at which the transmission is made. The transmitter sends a start bit to indicate the receiver to start reading. Then the data byte is transmitted, followed by a stop bit.

One other common form of serial communication is via the I²C bus. I²C bus stands for Inter-Integrated Circuit bus. The reason for calling this I²C instead of IIC is that mathematically I times I is I squared, writing I². Officially the bus is called "I squared C (I²C)", this became I²C to make it easier to write. The I²C system uses two communication lines; one data line and one clock line. The advantage of this method is that the communication speed does not need to be set on beforehand. Next to that, it is possible to get feedback on communication quality.

Batteries and power system

In order to provide power to your CanSat, you need to have an electrical power system. There are numerous ways to power your CanSat, but the most sensible way is to incorporate a battery. Other options, such as photovoltaic cells (solar cells) can be explored but are outside the scope of this chapter.

Battery types

A battery is a device which consists of one or more electrochemical cells which produce electricity by converting the stored chemical energy into electrical energy.

Batteries are available in two types:

- *Primary cells or single-use batteries*, which are cheap and can be bought in the supermarket or hardware store. The chemical energy in this type of battery is incorporated in the battery at the manufacturing process. This type of battery CANNOT be recharged.



Figure 27: a single use 9V battery, which can be bought at any local supermarket (source AFGA)

- *Secondary cells or rechargeable batteries*, which can be recharged by special charging equipment. It is absolutely necessary to use the proper charging equipment. The use of the improper charging equipment can result in fire and toxic fumes. An example of this type of battery is a lithium polymer battery which can be seen in Figure 28.
-

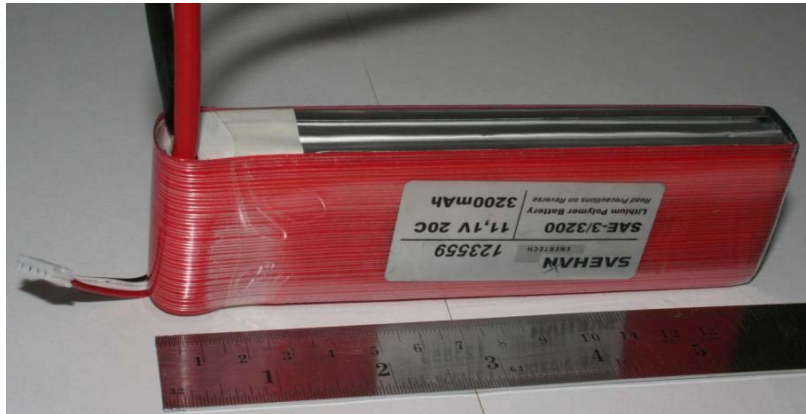


Figure 28: a lithium polymer battery, which is rechargeable with special balanced-charging equipment. (source Wikimedia.org)

Advantages and disadvantages

The rechargeable battery has several advantages and disadvantages with respect to a single use battery. It depends on the requirements you have on a battery which battery you will need for your CanSat.

Some considerations for choosing a battery type may be:

- A rechargeable battery can obviously be recharged during the project, which *could* result in a cost saving, because you do not need to buy new single-use batteries all the time.
- The energy density of a rechargeable battery is higher than a single use battery. This means that for example 100 grams of rechargeable battery can contain more energy than 100 grams of single use battery. This is a very important factor in aerospace engineering, where every gram counts!
- The disadvantage of the rechargeable battery is that you will need special charging equipment to charge your battery. This can be (very) expensive. Charging a battery can be dangerous, so always charge your battery on a non-combustible surface and never let it be unsupervised.
- Note: ALWAYS come to the launch site with fully charged batteries, or a fresh single use battery.

Calculations with a battery

The ESA CanSat kit needs voltages between 5.5V and 15V and has a power requirement of approximately 80 mA depending on the operation and the connected sensors.

When a device which needs 80 mA is connected to for example a battery of 550 mAh, this means that it can run for $\frac{550}{80} = 6.9$ hours. Of course, this will just be a rough estimation, since other factors, like resistance, current, battery internal resistance, battery temperature, etc. influence the actual battery lifetime. In general, the battery output voltage will drop during the lifetime of the battery. This is highly dependent on the amount of current that is consumed. Battery datasheets provide good reference for several types of current loading.

The standard CanSat kit is powered by a simple single use 9V primary cell, of which specifications can be found in Figure 29.

Battery tips and tricks

Having a good, stable and reliable voltage supply is absolutely essential for having a good and reliable CanSat. The CanSat electronics will only work when they are supplied with enough power. If the voltage drops only a fraction of a second under the 5.5V, strange things can happen, such as resetting microcontrollers or loss of signal. Make sure that the battery of the CanSat is fixed properly in the CanSat so that the battery leads are not momentarily disconnected when the rocket is accelerating, or the parachute is deployed with a high shock.

Another thing that could happen is that some subsystems of your CanSat (momentarily) use a lot of power. Due to this high power consumption, the voltage that the battery supplies to the system drops, which can result for instance in a reset of one or more microcontrollers.

Specifications

| | |
|------------------|--|
| Chemical system | zinc-manganese-dioxide (free of mercury and cadmium) |
| Dimensions | Diameter: 24.5 - 26.5 mm; 15.5 - 17.5 mm Height: 46.5 - 48.5 mm |
| Weight (approx.) | 45 g |
| Packaging | 1 battery in blister-pack with punch hole |
| Nominal voltage | 9.0 V |
| Capacity | 550 mAh (620 Ω , 24 h/d, 4.8 V) |

Example discharge times / Service life

| | | | |
|----------------------------|--------------|--------------|--------------|
| Load resistance | 180 Ω | 270 Ω | 620 Ω |
| Discharge mode | 24 h/d | 1 h/d | 2 h/d |
| End voltage | 5.4 V | 5.4 V | 5.4 V |
| Initial | 11.5 hrs. | 16.8 hrs. | 38.5 hrs. |
| After 12 months of storage | 10.5 hrs. | 15.2 hrs. | 35 hrs. |

Typical discharge characteristics

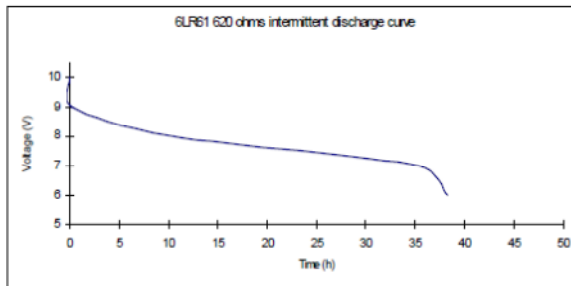
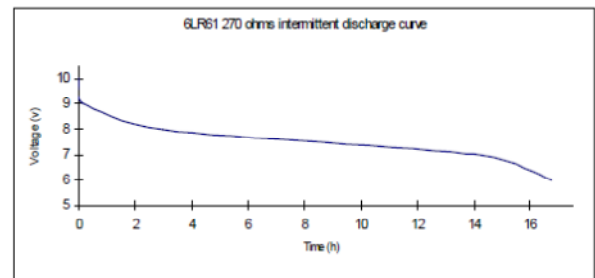
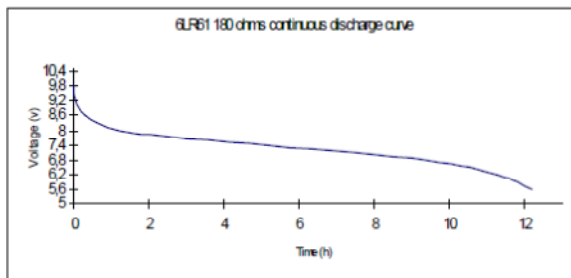


Figure 29: typical datasheet of a zinc –manganese-dioxide battery, which is supplied by the kit. (source AFGA)

It is definitely not recommended to use the provided battery for flight. It is a simple test-battery to be used just for that: testing the CanSat on the ground.

Introduction to soldering and circuit assembly

With a schematic diagram of an electric circuit completed it is time to go from theory to practice. To build an electric circuit, you need the components and a printed circuit board (PCB) to place them on. The PCB can either be one especially made for your circuit, or a general PCB on which you make the connections of your circuit yourself. This chapter will first show some component placement and connection methods for nonspecific PCB's. The design of custom made PCB's is not part of this document, although some possible advantages will be addressed. The last part of this chapter will provide a short introduction and checking method for soldering of the components.

A general form of nonspecific PCB's is the experimentation PCB with a solder grid. The most general version has a grid of holes with a spacing of 2.54 mm, or 100 mil. Every hole is surrounded by a bit of copper to solder the components. A circuit is built on such PCB by placing the components on the board and then using wires to connect them. These wires need to be placed such that the connections of the schematic diagram and built circuit are the same. Using short wires is better than long wires. The longer a wire, the more resistance it has. If the wire resistance becomes high it will influence the circuit and result in unwanted behavior.

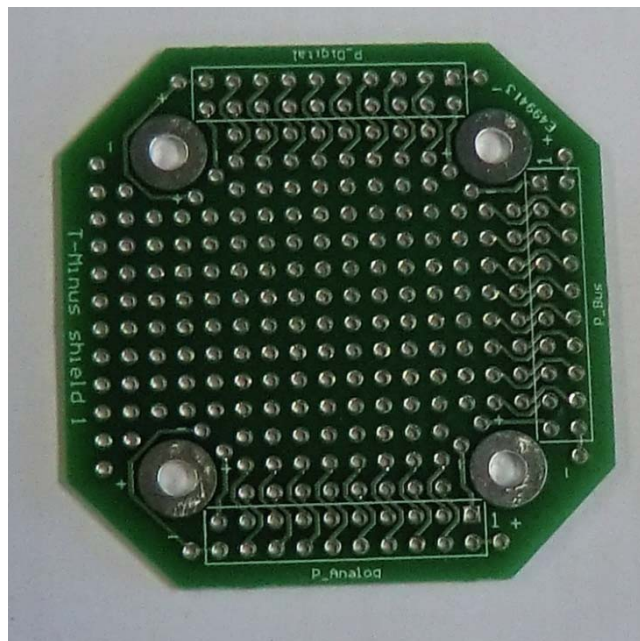


Figure 30: an empty CanSat kit sensor board (courtesy of T-Minus)

The PCB provided with the kit for the building of the primary mission is a semi-specific PCB. The PCB is designed in the shape of the main board with the solder-able holes aligned such that they can connect to the connectors of the main PCB. All the connections that go to the main board have an extra hole connected to them to make connecting wires easier. Looking closely at the board, the lines can be seen that make these connections.

Placing the components is a puzzle wherein the complexity depends on the amount of components and your personal demands on circuit size. Placing the components close together makes it harder to wire the connections, but it requires less board space. Leaving room for the wires will ease the soldering later while it increases the board space required. Building a PCB is planning ahead.

Design of a dedicated PCB is a method to make soldering much simpler and creates less of a hassle with wires to connect everything. Making a specific design provides more flexibility in the components that can be used. On the general PCB the grid is 2.54 mm, but most of the modern components are much smaller than that. There are many programs available for making PCB's. One that has a free license for non-commercial use is the computer program "Eagle". After the PCB is designed in such a program, it needs to be fabricated. This fabrication can be done by dedicated factories.

Soldering

Soldering is needed to make the components electrically connected. To solder the components they need to be heated and then solder needs to be added. The required soldering temperature depends on the type of solder used. Solder made for electrical circuits melts at around 183 degrees Celsius for leaded versions, or around 230 degrees Celsius for lead-free solders.

For making a good solder joint, it is important that both surfaces are heated to more than the melting point of the solder. If one of the surfaces is not hot enough, the solder will not make a good connection, which will result in a non functioning electric circuit. Making the components too hot will damage them.

Anatomy of a good solder joint

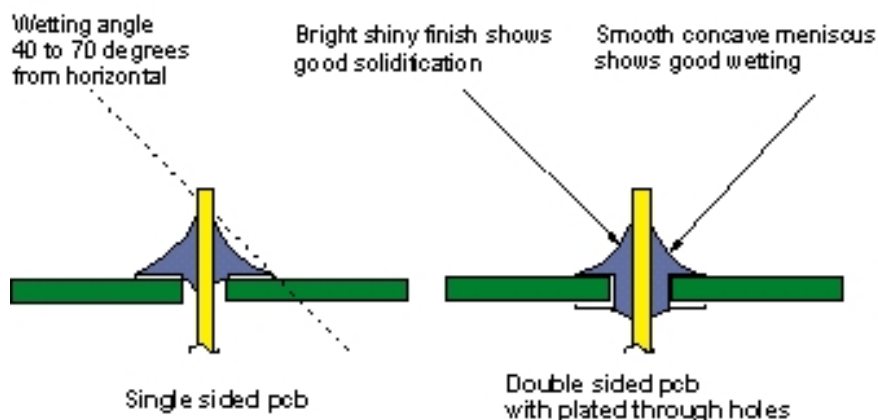


Figure 31: the anatomy of a good solder joint

The tip of the soldering iron is around 350 degrees. This is hot enough to destroy almost all components. Luckily, it takes quite some time to break a component during soldering. The time needed to make a good solder joint is much less than the time that the components can sustain the heat of the soldering iron. Generally speaking, it takes between 1 and 2 seconds to make a good solder joint. In Figure 31 to Figure 32 are several pictures of good and bad solder joints

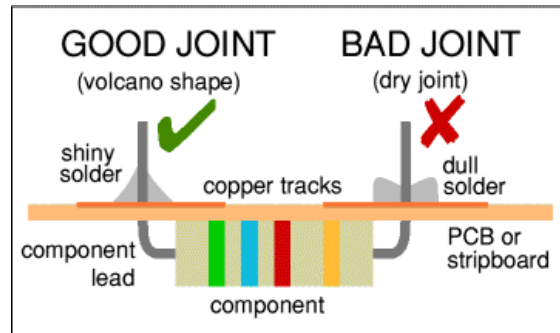


Figure 32: drawing of good and bad solder joint



Figure 33: photographs of bad soldering (courtesy of T-Minus)

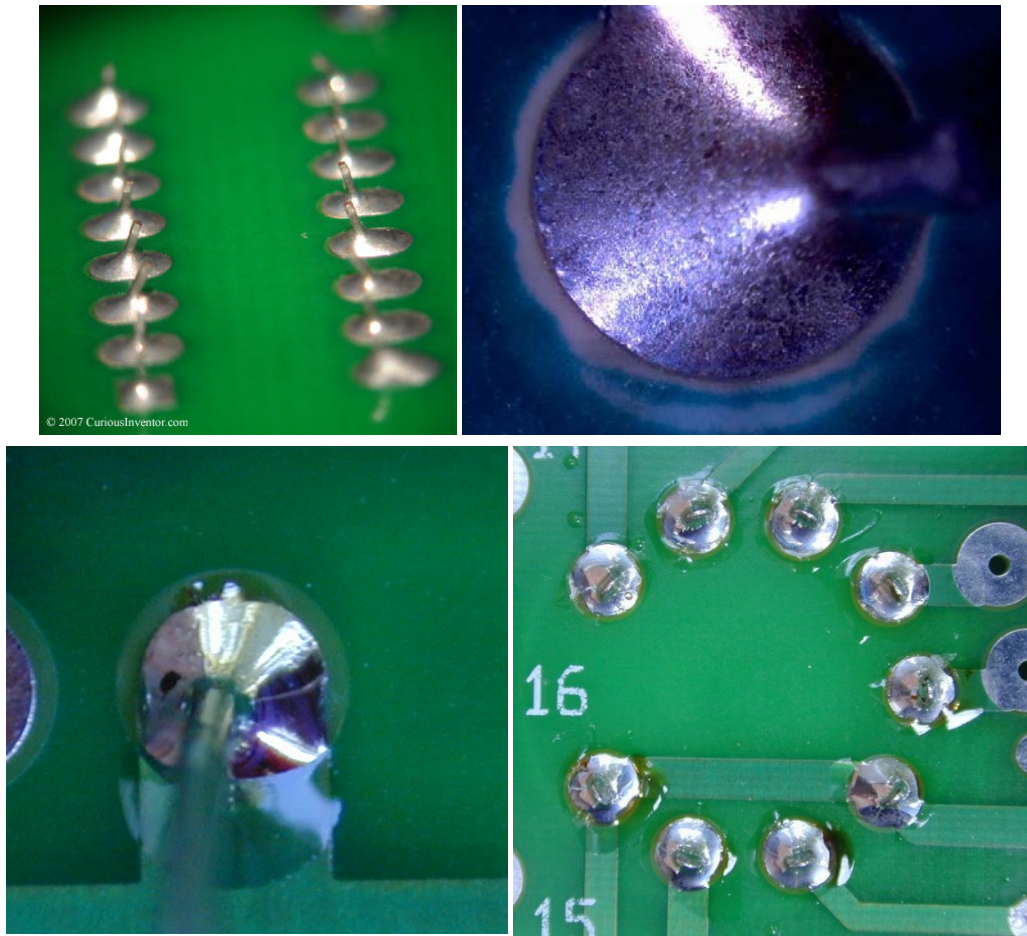


Figure 34: photographs of good soldering (courtesy of T-Minus)

Radio communication

Radio communication is sending information from one place to another, using electromagnetic waves, also called radio waves. Electromagnetic waves are generated at an antenna when an alternating electric current is connected to it. The antenna transforms the electric current into electromagnetic waves. At the receiving end of the communication, the waves are transformed back into electric current by an antenna.

Using the radio waves to transfer information means that the information needs to be added to the radio frequency used. Adding this information is called *modulation* and can be obtained in several ways. The most basic form is to transmit a (*carrier*) frequency or not. This is called continuous wave (CW) communication. The most used form of CW is Morse code. The biggest drawback of this is that the information transfer rate or *baud rate* is very low.

There are many other forms of modulation, such as AM and FM. These are used by radio stations. With AM (amplitude modulation), the information is made to change the *amplitude* of the carrier frequency. In FM (frequency modulation), the *frequency* of the carrier is changed, as depicted in Figure 35. The advantage of FM over AM is that the signal strength does not interfere with reception.

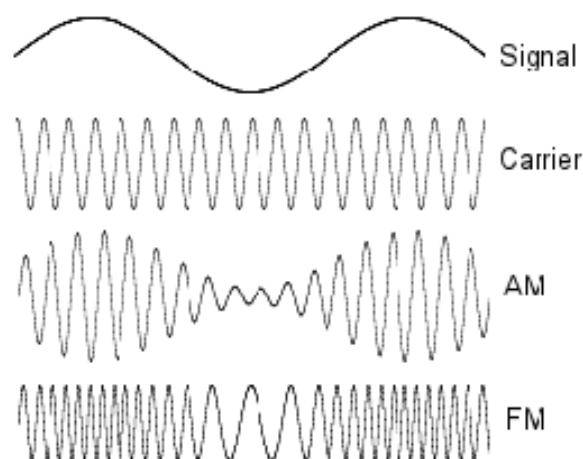


Figure 35: the difference between AM and FM modulation

The CanSat kit has a transmitter that modulates with Frequency Shift Keying (FSK). This means that it is transmitting a frequency when a logic 0 is transmitted and a different frequency if a logic 1 is transmitted, as depicted in Figure 36. There are many other forms of modulation like QPSK where two bits are transmitted simultaneously.

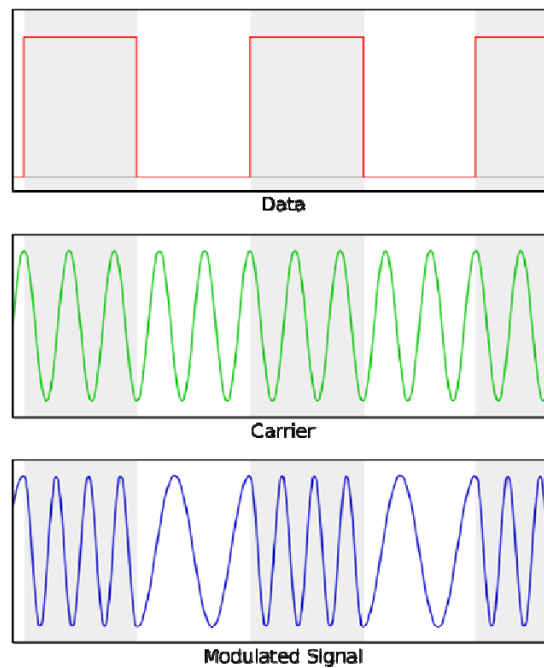


Figure 36: frequency shift keying FSK

The quality of the radio link depends mainly on three aspects: the transmit power, the receiver sensitivity and the used antennas. The only aspect that can be influenced by the CanSat team is the antenna. The other aspects can be influenced, but then a different transmitter and receiver are required, which is beyond the scope of this document.

There are two antennas used in receiving the information from the CanSat: the first is the antenna on board the CanSat, the second is the antenna used at the ground station. The antennas need to be made with different requirements, although the frequency of operation is similar for both antennas. The antenna on board the CanSat needs to be isotropic (or as much as possible), which means that it transmits the same amount of power in all directions. The antenna connected to the ground station can be pointed towards the CanSat, and it can therefore be made as a high-gain directional antenna, which receives more electromagnetic waves from one direction than from another.



Figure 37: an “Arrow” which is a Yagi antenna for operation at 2 different frequencies

Figure 37 shows a directional Yagi antenna that operates at two different frequencies. The antenna has a 7 elements Yagi for 433 MHz and a 3 elements Yagi for 145 MHz. For receiving the CanSat, building a Yagi antenna might be a very good option since it can be constructed relative easily, using wood and copper tubes. There is plenty of information on the internet to build a Yagi antenna.

The CanSat antenna needs to be sufficiently robust to survive the launch on a rocket. For the CanSat, a quarter-wave wire antenna works very well. The quarter-wave describes the length of the antenna in reference to the operation frequency. The transmitter of the CanSat kit works at around 434 MHz. the precise frequency depends a bit on what team you are in. This is done to protect each other from interference. The required length of the antenna can be calculated by using the following equation

$$L = \frac{c}{4f} = \frac{(3 \cdot 10^8)}{(4 \cdot 434 \cdot 10^6)} = 0.173m$$

Wherein:

- L is the required antenna length (1/4 wavelength) [m]
- C is the speed of light (300.000 km/s) [m/s]
- f is the operating frequency [Hz]

The formula shows that the length of the antenna for 434 MHz should be around 17.3cm. The wire can be soldered to the antenna contact of the transmitter board directly, or, when using a coaxial cable, the antenna can be placed some distance away from the board. When using a coaxial cable, the last 17.3cm the outer conductor needs to be removed to form the actual ¼ wavelength antenna. Protect the insulation material, as electric contact with metal surfaces might damage the transmitter.

Introduction to programming

There are many forms of programs, such as computer programs, websites, mobile phone apps and many more. These programs are used for many different applications from, running your microwave oven to allowing you to check your bank account on the internet. All programs have one thing in common: they are written using a programming syntax. This syntax is often called the programming language. The syntax is a method to describe what the program needs to do. Depending on the application, a program either needs to be compiled before use or it is compiled while using the program. Most webpages use languages that allow the web browser to compile or read the programming language directly. Languages that can be used for this are HTML or JAVA. Computer programs need to be compiled before use to change the program syntax in to instructions that the computer understands.

Every (Computer) processor has an instruction set of binary codes used by the processor to undertake certain actions. This type of programming is used during the CanSat competition. The micro controller provided in the CanSat kit is a small computer. Micro controllers are used in many systems, like robot welding machines. The difference between a micro controller and the processor in your computer is that a controller is a processor with hardware control and memory in one component. During the CanSat competition the C programming language will be used and Arduino will be used as compiler.

```
1.     int function ( char a )
2.     {
3.         char b, C;
4.         int Data = 10;
5.
6.         // comment
7.         b = a + Data;
8.         C = b - 1;
9.         Anotherfunction( C );
10.    return b;
11.    }
```

Above, a short example of a program written in C is given. To describe the entire language in this document will not be possible and also not useful. This is mainly because Arduino uses several libraries to make life simple. Therefore this document will describe the bare minimum, while more information can be found on the Arduino website or more general all over the World Wide Web. Many examples can also be found in the Arduino program.

The programming language can mainly be separated in 4 groups: functions, variables, operations and formatting.

- Functions are bits of code that do several tasks. Functions can be premade or user made. A function is “called” during the program if the task it is made for is required.
- Variables, as the name implies, are used to store values that might change during the program. A variable in C needs to be defined at the beginning of a function (local variable) or before the first function (global variable). There are several types of variables, depending on the size they have.
- Operations determine what happens in the program, such as adding two variables. Operations can also compare variables to go through certain code only in certain situations.
- Formatting is required for the computer to understand what you want. Some of the formatting is also used to make a program more readable for users. Two of the (many) formatting aspects are the semicolon (“;”), which is used to end most of the programming lines, indicating to the computer that the statement before must be done before continuing. The “//” this tells the computer that everything behind the “//” and on the same line is comment, this is used to explain certain pieces of code.

Using the short example above lets describe what an operation is. The program shown is a function called “function”. If program calls “function” line 1 tells how this function is called. In this case the function is defined as an integer (int). This means that the function will return a 16 bit value when finished. One often used definition is “void” if no return value is needed. The second part of line 1 defines the value that is given to this function when called. Here the function needs a character, or 8 bit value, which is then placed in variable “a”.

The “char a” and “char b, C” parts of line 1 and 3 are the definition of local variables. These variables can be used inside this function and will be forgotten by the program when this function is left. Line 3 defines two values as “char” without any starting value. Line 4 defines the variable “Data” with a value of 10 to start with.

Lines 2 and 11 define where the function “function” begins and ends with the brackets ‘{’ and ‘}’. By using a tab with the lines in between it is very clear where this function starts and where it ends. This also makes it easier to see if the brackets are placed correctly. Line 5 is an empty line used to make the program readable. Line 6 is a comment line used for the same purpose.

Lines 7 and 8 are operations, in this case small calculations to change variables. Line 9 is a call to the function “anotherfunction” where the value of variable “C” is given to this function. Line 10 determines what value the function “function” returns when finished.

Data inconsistencies

The above program has 2 problems with variables. The first one is on line 7. In this line, an integer and a character are added together and the result is placed in a character. The problem is that the integer is 16 bits and this is placed in an 8 bit variable. So either b needs to be an integer or Data a character. The second problem is that function returns an integer while the return line only provides a character. The compiler will either provide a warning or error to indicate this mismatch.

Introduction to data analysis

At this point, you are at the stage where your CanSat is fully operational. You are able to perform measurements with the sensors and your CanSat can send the measurement data down to your ground station, where they are received. If everything went well, you received a stream of data lines. Each line consists of a time mark, indicating when the measurement was taken, and some numeric values of the voltages that your sensors recorded. From this data set, you want to deduce the actual quantities that your sensors measured, such as pressure and temperature. Then you want to present these quantities in a nice and clear way. This chapter provides you with guidelines on how to perform these steps.

From data to measurements: calibration

The data that are received so far do not provide good insight into the quantities that are actually measured, such as air temperature: they are just voltages as obtained from the sensor outputs. To obtain valuable measurements, the voltages will have to be converted into the measured quantity. This can be done by determining a calibration curve for the sensor. A calibration curve essentially tells what output voltage can be expected when the sensor is subjected to a given temperature. This means that the curve can be used in the reversed way as well: it tells you what temperature the sensor senses when the output voltage is a given value. Therefore, measurements can be deduced from the data with this curve.

In most cases, the relation between the sensed quantity and the output voltage is linear, which means that it can be expressed as:

$$(0.8) \quad Q_{meas} = a \cdot V_{out} + b$$

Where

- Q_{meas} is the value of the measured quantity (for example temperature) [K]
- V_{out} is the output voltage of the sensor [V]
- a is the *calibration gradient* [K/V]
- b is the *calibration offset* [K]

Calibration of the sensor means therefore determining the values of a and b . For some sensors, this is very easy: just check the data sheet of the sensor. The gradient and offset should be given here. However, in most cases, only a range of values is given: the gradient and offset may be in between a certain minimum and maximum value. Determining the exact values is therefore necessary.

The equipment needed to perform a calibration is a source of the quantity that is measured (for the temperature sensor, this is a device that can give the sensor a given, well-defined temperature, for example a glass with water on a hot plate), and a pre-calibrated sensor, such as a thermometer. The thermometer and the sensor are both placed in the glass of water and the output from the sensor as well as the indicated temperature on the thermometer is monitored and noted down. Now, the temperature of the water is gradually increased by turning on the hot plate. At given time intervals, both the sensor output and the reading from the thermometer are noted. The calibration can be stopped when 5 – 10 measurement within the desired range of temperatures are obtained. An example of the noted values is given in Table 4.

Table 4: Example calibration curve measurements

| Time of measurement [s] | Temperature of thermometer [°C] | Temperature sensor output voltage [V] |
|-------------------------|---------------------------------|---------------------------------------|
| 0 | 15 | 0.60 |
| 30 | 25 | 1.53 |
| 60 | 34 | 2.35 |
| 90 | 41 | 3.05 |
| 120 | 48 | 3.63 |
| 150 | 53 | 4.10 |
| 180 | 56 | 4.45 |
| 210 | 59 | 4.68 |
| 240 | 60 | 4.80 |

Now, the measurements are drawn into a graph, with the sensor voltage on the X-axis and the temperature on the Y-axis. The points should form a more-or-less linear line, as indicated in Figure 38: Example calibration curve. When this is done in a computer program, usually the possibility exists to add a so-called “trend line”. This is a given function (linear, polynomial, exponential, etc.) of which the shape parameters are automatically adjusted such that the best fit of the curve with the measurements is obtained. In this case, a linear trend line is fitted, as indicated in Figure 38. The options “display equation on chart” and “display R² value on chart” are enabled. With the first option, the used formula is displayed, while the second option shows the so-called R²- value. This value indicates how well the curve fits all the measurement points. A value of 1 indicates a perfect fit, the lower the number, the worse the fit. One can observe that the function of the linear fit has the same form as equation 1.8. This means that the values of a and b can be read directly from the displayed function. In this case, they are 10.743 K/V and 8.6007 K respectively. Now, the calibration curve is determined, and the actual data obtained from the CanSat can be converted into real measurements, by applying equation 1.8.

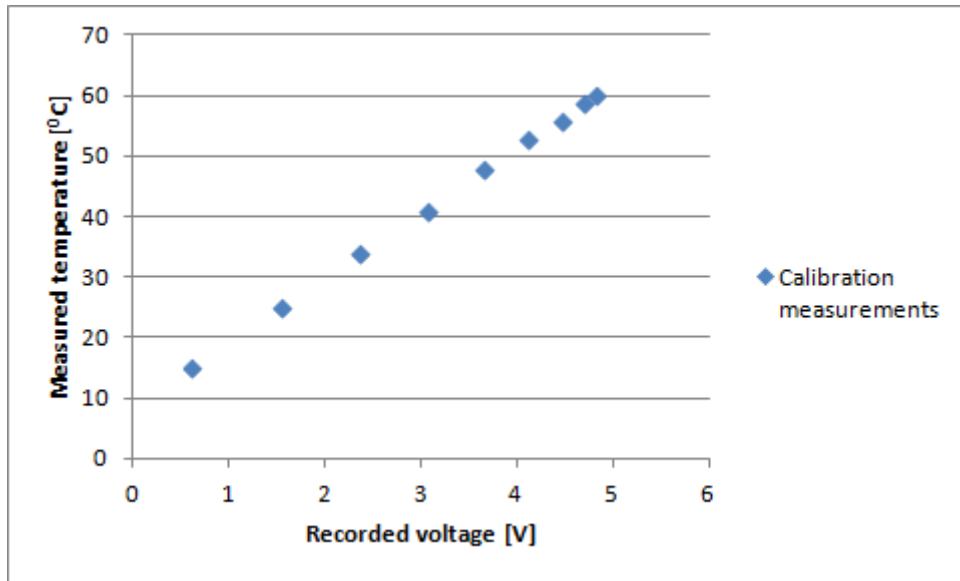


Figure 38: Example calibration curve

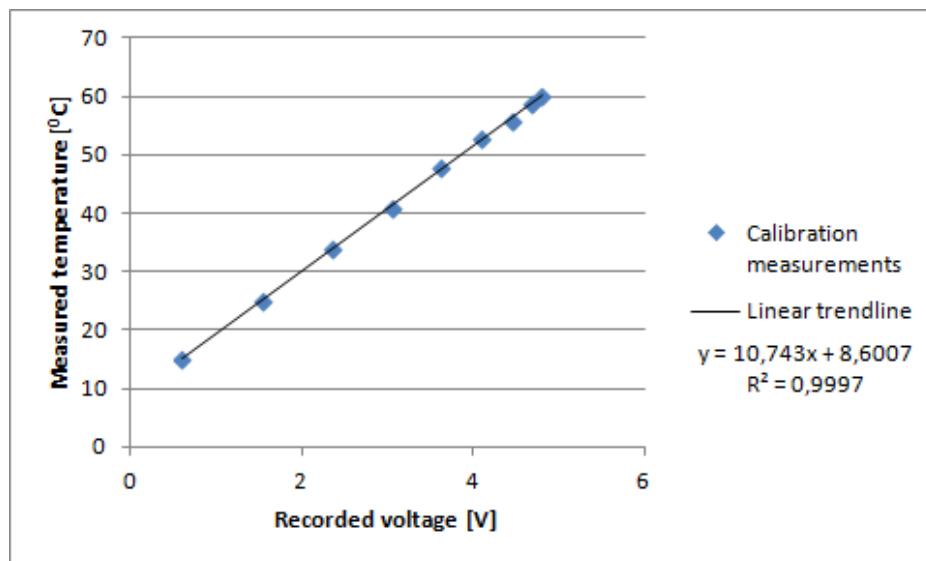


Figure 39: Calibration curve with trend line

Results presentation

Now that the measurements are obtained, they have to be presented in a clear and unambiguous way, so that other people can understand them and the conclusions that are drawn from it. The most basic way to present results is the table. An example is Table 5. The measured quantities are displayed in the columns, while each measurement point is displayed in one of the rows. It is important that the columns are labeled, so that it is clear what the meaning of the presented values is. The labels contain the quantity (time, temperature and voltage, respectively), the object that has been measured (time, thermometer, sensor) and the unit used to express the measured values (s, °C, V).

A title or caption can be added to clarify the conditions in which the measurements were taken and how they were obtained. Finally, the grid lines are displayed for readability.

It is important that the displayed values have the right significance. This means that if the measurements of the thermometer are taken with 1 °C accuracy, they should be displayed with 1 °C accuracy, hence 15 °C, instead of 15.0 °C. This is especially important when a certain conversion via a formula is used to obtain the displayed value. If for instance, the output voltage of the sensor is read as being 3.63 V, and the corresponding temperature is calculated with formula 1.9, the outcome would be:

$$(0.9) \quad T = 10.473 \cdot 3.63 + 8.6007 = 47.59779 [^{\circ}C]$$

However, since the output voltage is measured with only three significant numbers, the corresponding temperature should be rounded to three significant numbers as well, hence a value of 47.6 °C should be displayed.

Table 5: Measurements of temperature sensor calibration 1

| Time of measurement [s] | Temperature of thermometer [°C] | Temperature sensor output voltage [V] |
|-------------------------|---------------------------------|---------------------------------------|
| 0 | 15 | 0.60 |
| 30 | 25 | 1.53 |
| 60 | 34 | 2.35 |
| 90 | 41 | 3.05 |
| 120 | 48 | 3.63 |
| 150 | 53 | 4.10 |
| 180 | 56 | 4.45 |
| 210 | 59 | 4.68 |
| 240 | 60 | 4.80 |

Next to the table, a second convenient way of displaying measurement results is by means of a graph. An example is given in Figure 40.

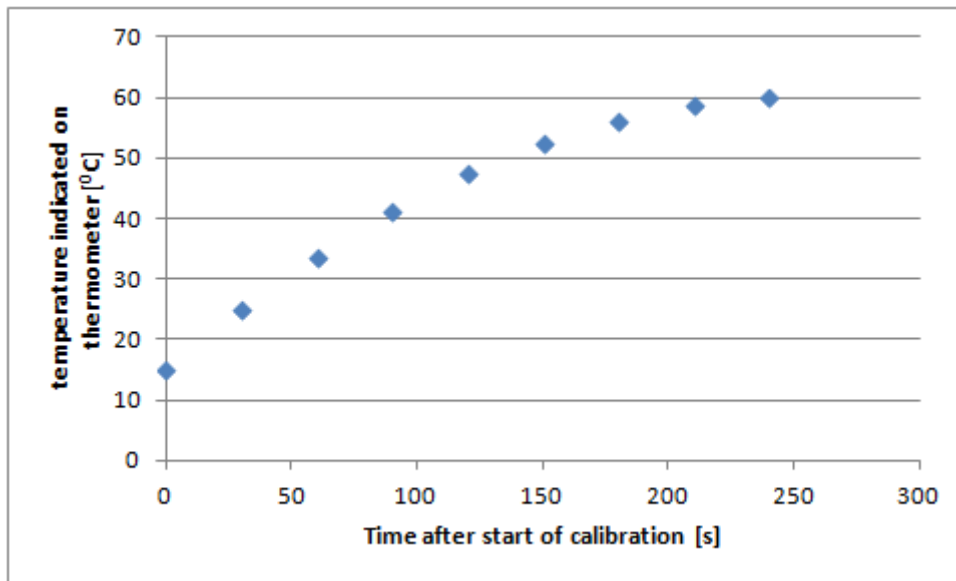


Figure 40: example measurement graph

A graph is composed by an X and Y-axis, with the values of one quantity at the X-axis and the values of the second quantity on the Y-axis. Usually, the independent quantity is displayed on the X-axis, while the dependent quantity is set on the Y-axis. It is important that the range of both axes is chosen wisely: all measurements should be displayed and the entire graphing field should be used. If necessary, a logarithmic scale can be chosen instead of a linear one, so that a wider range of measurements can be displayed. Discrete (= not continuous) measurements should be displayed by a marker. If desired, the markers can be connected by lines. Continuous functions may be indicated by a continuous line only. The axes shall be labeled, just as the columns of a table, with measured quantity, object and unit. If more than one data series is displayed, a legend should be provided, so that the series are easily distinguished. It is important to remember that some colors, for example dark blue and red, are not easy to tell apart when printed in black-and-white or grey shades. If the range of the one data series differs significantly from the other, a second X or Y axis may be added for clarity, as visualized in Figure 41. Grid lines may be added to the graph for easier reading. Finally, a title or caption can be added to provide more information on the displayed values.

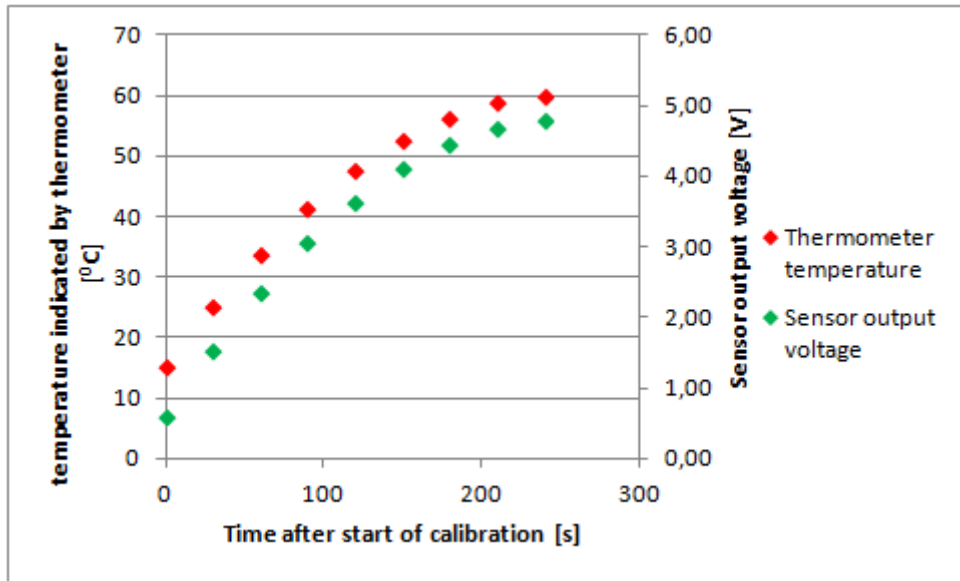


Figure 41: Example measurement graph with two Y-axes

Other resources and further information

http://upload.wikimedia.org/wikipedia/commons/0/07/Lithium_polymer_battery_%2811.1_volts%29.jpg

http://www.produktinfo.conrad.com/datenblaetter/650000-674999/650411-da-01-en-AGFAPHOTO_9V_E_BLOCK.pdf

<http://www.conrad.nl/ce/nl/product/650411/>

http://upload.wikimedia.org/wikipedia/commons/e/e6/USMC_Paratrooper.jpg

http://en.wikipedia.org/wiki/File:Ram_air_square.jpg

<http://forth.aero.cst.nihon-u.ac.jp/activity/e-a-pad.html>

http://www.madehow.com/images/hpm_0000_0005_0_img0132.jpg

<http://www.nakka-rocketry.net/xchute1.html>
