Thesis Milieu- en Natuurwetenschappen

# The use of solar powered UAV’s in measuring air quality

Ronald Muijtjens

3032760

Supervisor:
Boudewijn Elsinga MSc

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## Summary

This thesis discussed the possibility of using solar powered UAV's as a means of measuring air quality. As Smidl has shown it is possible to use a UAV in case of a single source of pollution in addition to existing ground-stations. Two UAV's can achieve the same quality measurement data as 30 ground-stations. However those UAV's cannot stay airborne forever while ground-stations can measure day and night. Geo-stationary satellites can observe the same spot continuously but are inaccurate when clouds are blocking the view. Airborne measurements conducted by weather balloons only create a vertical profile whereas airplanes and zeppelins can give 3d profile of the pollution.

This thesis also presented a guideline which can help with designing (and making) a solar powered UAV capable of doing air quality measurements in the boundary layer. It has the advantage to measure everywhere as long as the sun shines. With increasing miniaturization of electronics better sensors can be put on this UAV. Advancements in photovoltaic techniques will ensure that the UAV also flies in the winter or less clear skies. As shown in chapter 3, flight on solar power is only possible around noon for the months April until September and in June it is possible (with the 24.2% cells) to fly solely on solar power from 9am till 3pm.The 30.8% cells can achieve a continuous flight from 8am till 5pm in June. Further advances in solar cell efficiencies can make year round flying on solar power possible. Flying from dawn till dusk is not possible solely on solar power, the irradiance of the sun is just too low for flight. With the use of batteries flight can be extended so that a flight from dawn till dusk becomes possible and with better batteries day and night flight on a fixed altitude might eventually be possible.

A UAV can be a cheaper and less polluting alternative for airplanes, weather balloons and zeppelins in case of (sudden) single-point pollution but its flight time is the limiting factor. A UAV can also be made smaller and lighter so the availability of a runway is not an issue when operating it. When solar cells are added it can be an autonomous airborne measuring device during day-time and be a good addition to existing measurement stations.

## Contents

# Introduction

Current air quality data collecting happens mostly on the ground with ground based stations, fixed position as well as mobile stations. Airborne measuring stations are mostly only used in cases of severe accidents for a post-accident analysis as it is too dangerous to send human-operated aircrafts into the polluted area (Smidl, 2013). Large UAV's are already used in different fields of research, but those need a small runway to land and they run on gasoline.

The use of UAV's (Unmanned Aerial Vehicle) is increasing and with it increasing demand for its capabilities. In Japan, for instance, Yamaha Motor sells up to 300 of its RMAX unmanned helicopters every year for crop spraying on private land (Stafford, 2007). Conservationdrones.org is an organisation which aims to create an affordable and durable UAV for conservation (and other) purposes. At the moment these UAV's (with a weight of 2a3kg and a wingspane of around 2 meters) have an average flight time of 40 a 50 minutes and a range of 50 km. For increasing the range of the UAV, alternative power sources have to be used. The UAV's from Barnard Microsystems run on gasoline and is able to fly for more then 7 hours with a range of over 700km. But it weighs around 27kg, has a wingspan of 4 meters and therefor needs a small van for transportation. Another option is putting more batteries on the UAV, but that means a heavier craft which in turn leads to shorter flight times. So, the best solution would be to be able to recharge the batteries while in flight, for example with solar cells. Projects like SenseSoar already proved that sustainable flight (day and night) is possible, AtlantikSoar will prove that long distance flight with solar powered UAV's is also possible. The next step will be to have a solar powered UAV capable of carrying research equipment. With increasing efficiencies and lower prices of solar cells it is becoming a viable alternative for gasoline powered endurance flight. The main focus of this thesis will be the usability of a solar powered UAV in The Netherlands which is small enough to be used without a landingstrip, which can be carried and operated by one person and is capable to conduct air quality measurements in the boundary layer. The main question of this thesis is:

*What are the benefits of solar powered UAV's over traditional air quality measuring tools?*

First an overview of current air quality measurement techniques is given. In the second chapter the history of solar power and solar powered flight is shown. The photovoltaic effect is explained and how to use it to propel an airplane in the air. The chapter ends with the amount of solar irradiance in The Netherlands and which photovoltaic (PV) techniques could be used for a solar powered UAV. In the last chapter (chapter 3) the feasability of a solar powered UAV is studied in detail.

# 1. Air quality research

## Pollutants

The most common pollutants in the air are: Ozone (O3), Nitrogen Oxides ($NO_x$), SulphurDioxide ($SO_2$), Lead, Carbon Monoxide (CO) and Particulate Matter (PM). The European Commission has issued a guideline in 2008 concerning cleaner air. In this guideline limits for several pollutants are set to reduce the pollution to levels which are less dangerous for humans in particular and for the environment to reduce them as low as possible. Another decree is to monitor the air quality and to improve this monitoring (Guideline 2008/50/EG). The limits for these pollutants are shown in Table 1.

| Pollutant | Maximum pollution level |
|---|---|
| O3 | AOT40, 40 particles per billion particles (80µg/$m^3$). |
| $NO_x$ | 140µg/$m^3$ |
| $SO_2$ | 75µg/$m^3$ |
| Lead | 0.35µg/$m^3$ |
| Co | 7 mg/$m^3$ |
| PM | 35µg/$m^3$ |

**Table 1 Maximum pollution levels (European Commission Guideline 2008/50/EG)**

## Measuring pollutants

Instruments using physical scientific measurement techniques, such as chemiluminescence, UV fluorescence, IR absorption and Differential Optical Absorption Spectroscopy (DOAS), are used to measure the levels of these pollutants. Ozone is measured by its absorption of ultraviolet (UV) light or by the electrical current or light, produced in a chemical reaction involving ozone. To determine NOx values, No and $NO_2$ need to be measuredwith an infrared gas analyser. Sulphur Dioxide can be measured on four different ways: ultraviolet fluorescence method, conductimetric method, coulometry and flame photometry. Carbon Monoxide can be measured using infrared and electrochemical instruments. Inertial separators are used to measure Particulate Matter when other, non-dangerous particles, are also present in the air. These particles are then separated and the air can be measured with, for instance, a TEOM (tapered element oscillating microbalance).

There are different ways of measuring air quality, which can be divided into three groups: ground-based, air-based and satellite-based measurements.

Ground based:

The first measurements were done with ground stations. In 1961 the United Kingdom established the world's first coordinated national air pollution monitoring network which measured black smoke and sulphur dioxide. Since then, many countries have developed such a network. In The Netherlands a national air pollution monitoring network was established in 1973 which could measure sulphur dioxide. This network gradually expanded to 244 measuring locations in 1983.By then these locations could also measure CO, O3 and NOx. Thanks to increasing knowledge on air quality and the ability to use models, the number of measuring stations declined to 58 in 2007. The last few years more monitoring stations are set-up due to legislation.
The Cabauw-tower is a 213 meter high tower near the town of Cabauw, The Netherlands. It's owner, the KNMI (KoninklijkNederlandsMeteorologischInstituut), uses the tower to establish relations between the state of the atmospheric boundary layer (ABL), land surface conditions and the general weather conditions for all seasons (KNMI, 2013).

A few types of devices are commonly used when measuring air quality. Different measuring stations need different measuring devices. Ground stations require sturdy devices which are easy to operate and maintain, airborne stations require lightweight devices. Below are a few devices commonly used in measuring stations:

- TEOM for Particulate Matter 33kg (ground station/truck)
- HVS DHA-80 for Particulate Matter: 60kg (ground station/truck)
- CPC TSI 3025 for nitrogen-particles (on the BAe-146 airplane): 12.5kg (ground station/truck)
- MAAP (ThermoTMCarusso 5012) for black carbon: 28.6kg (ground station/truck)
- Aethalometer (Magee AE 42) for black carbon: 11.3kg (ground station/truck)
- Met One Aerocet 531: 0.88kg (handheld device/UAV)
- Met One Model 804: 0.60kg (handheld device/UAV)

A new development is gas-sensing with field-effect transistors (Andringa 2013) which makes it possible to, for example, put a small sensor in a mobile phone or on a car and create a large mobile sensor network which can provide real-time air quality data.

Airborne research:

Weather balloons can give a good vertical profile of air quality from ground level to the stratosphere. Airplanes are capable of measuring air quality at different heights and at different location in a short period of time (Ottar, 1986), (Nickerson, 1992), (Stohl, 2007). NASA has several airplanes which can provide airborne measurements to support ground-based measurements. But for the amount of money it costs to fly one mission with an airplane, a small UAV can be bought and flown several times (Barnard Microsystems, 2012).

The PEGASOS-project is a Europe-wide project involving numerous scientific institutes and universities across Europe which aims at improving knowledge on interactions between climate change and air quality. The PEGASOS is a zeppelin with numerous measurement devices on board which will measure air quality on specific locations and are compared with simultaneous ground station measurements.

Satellite research:

NASA and its international partners operate several Earth-observing satellites that closely follow one another along the same orbital "track." This coordinated group of satellites, constituting a significant subset of NASA's current operating major satellite missions, is called the Afternoon Constellation, or the A-Train for short. The satellites are in a polar orbit, crossing the equator northbound at about 1:30 p.m. local time, within minutes of oneanother. This allows near-simultaneous observations of a wide variety of parameters to aid the scientific community in advancing theknowledge of Earth-system science and applying this knowledge for the benefit of society. Six satellites currently fly in the A-Train: Aqua, CALIPSO, PARASOL, GCOM-W1, CloudSat, and Aura. The MODerate resolution Imaging Spectro-radiometer (MODIS) on board Aqua satellite uses images to measure aerosols. These images capture the distortion created by interaction between electromagnetic radiation from the earth's surface and fine solid and liquid particles.Thisprocess takes place in the atmosphere before the radiation reaches the satellite sensors. The observed distortion can be converted into a measure of aerosol optical depth (AOD), which has been established scientifically as a good predictor of suspended particles in the atmosphere. The CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) provides high-resolution vertical profiles of aerosols and clouds. Aura has four instruments on board to measure ozone-trends, air-quality changes and their connection with climate changes. PARASOL carries onboard a radiometer/polarimeter called POLDER, which stands for Polarization and Directionality of the Earth's Reflectances. POLDER is designed to improve our knowledge of the radiative and microphysical properties of clouds and aerosols by measuring the directionality and polarization of light reflected by the Earth-atmosphere system. The Global Change Observation Mission-Water (GCOM-W1) "SHIZUKU" satellite observes the earths' water-cycle. The Cloudsat observes the vertical structure and overlap of cloud systems and their liquid and ice-water contents. OCO-2, which will observe CO2-levels, is scheduled to join the configuration in 2014 (NASA, 2013).

The European Space Agency developed the Envisat, the most advanced environmental spacecraft ever built, and the largest earth observation satellite put into space. It was capable of collecting data of land, water, ice and atmosphere. The Envisat ceased operation in April 2012 after being in service for 10 years (ESA, 2013). Data from the Envisat and the Aura satellite was used to make Dutch air quality available in Google Earth, thanks to SRON and the KNMI (KNMI 2007).

Satellites can only be used when there is no cloud cover and the best results (when compared with ground data) are achieved when relative humidity is 40%-50% and the mixing height is between 100m and 200m (Gupta, 2006). Most satellitesare not in a geostationary orbit thereforethey cannot give continuous measurements of one location and are not as accurate as ground stations. Improvements in accuracy are still being made but satellites remain dependant of verification with ground stations (Gonzales, 2000), (Costa 2002), (Duclaux, 2002), (Engel-Cox, 2004), (Al-Saadi, 2005), (Gupta, 2006), (Chan, 2008), (Hoff, 2009), (Wang, 2010), (Kulmala 2011),

# 2. Solar Power

The goal of this chapter is to make a selection of usable solar cells for an UAV. First a short history on Solar Cell technology development will be given, after which the photovoltaic and photoelectric effect will be explained. This chapter will end with an overview of present day technology and a choice will be made on which technology can be used.

## History of Solar Flight

Two major discoveries in the 19th century were very important in the development of photovoltaic cells. First, in 1839 the nineteen year old Edmund Becquerel discovered the photovoltaic effect while experimenting with an electrolytic cell made up of two metal electrodes. This showed the relationship between light and electronic properties of materials. Second, in 1887 Heinrich Rudolf Hertz discovered that ultraviolet light was capable of altering the lowest voltage possible which was still able to cause a spark between two metal electrodes. In 1904 Albert Einstein published his work on this effect, the photoelectric effect, and in 1916 R. A. Millikan provides the experimental proof (Petrova-Koch).

The development of the photovoltaic cells starts when Walter Schottky presents a theoretical concept for semiconductor PV. This will eventually lead to the pv-cells we know today. In the 1950's the main application of solar cells was in space. From the 1960's applications on earth were developed. At the same time the oil production in the United States peaked, which was a prelude to the first oil crisis in 1973. In 1979, during the Iranian revolution, disrupted oil production in Iran resulted in the second oil crisis (Figure 1). These two events sparked many projects searching for alternative energy sources, including the sun. In 1976 the first thin film solar cell with an efficiency of 1% was demonstrated and in 1986 ARCO Solar released the first commercial thin film power module (Petrova-Koch). In the 1990's and 2000's photovoltaic cells became more efficient and in the 2010's thanks to China's industrialization they became much cheaper (Washington Post, 2012).

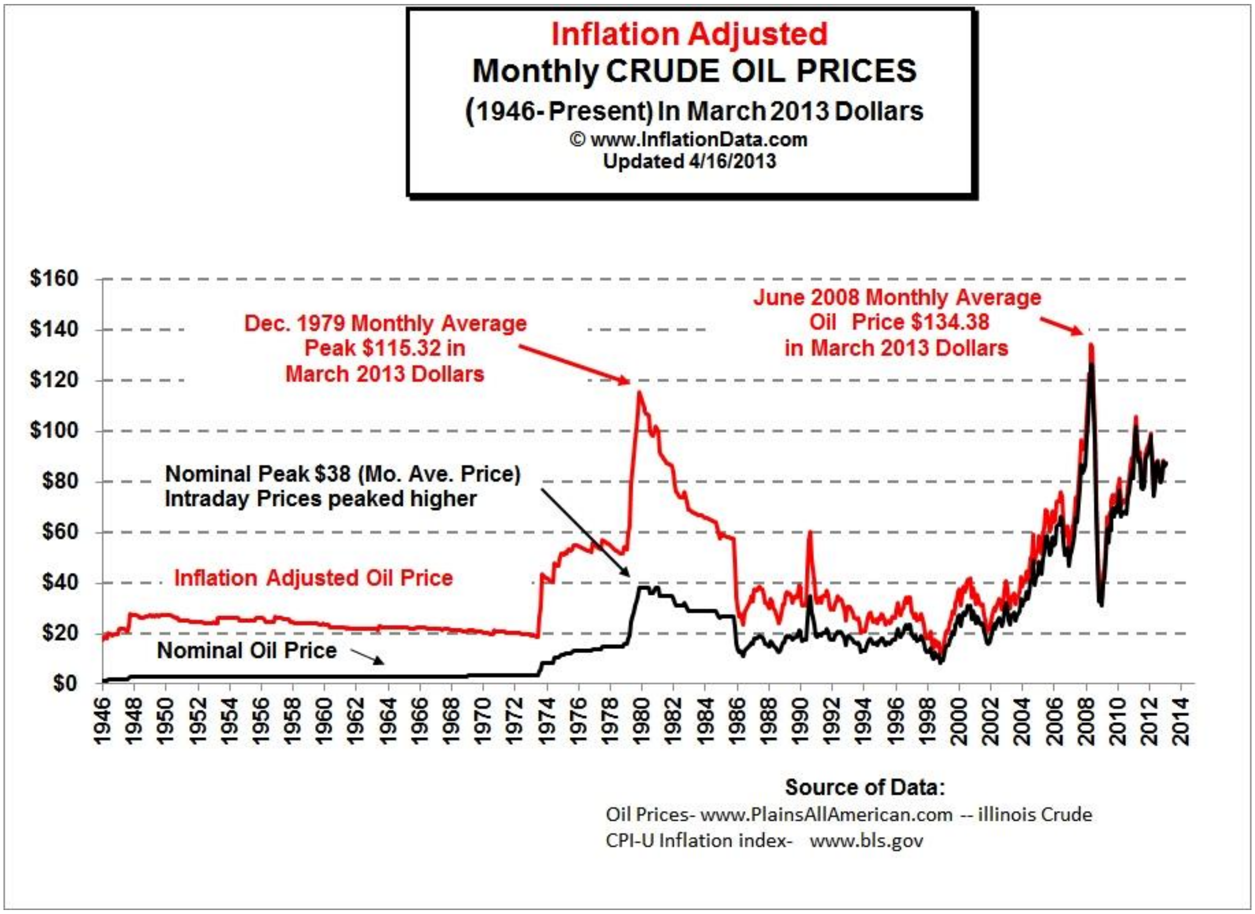


**Figure 1 History crude oil prices (Inflationdata.com, 2013)**

With efficiencies increasing every year (Figure 5), people began to dream of eternal flight. Pioneering work was done by R.J. Boucher on the 4th of November 1974 with the first solar powered flight in history. The Sunrise I flew for 20 minutes and reached an altitude of 100 meters. Unfortunately Sunrise I was damaged in a sandstorm a few months later and never flew again. Its successor, Sunrise II, crashed due to problems with the control system. These are examples of problems in the early development of solar powered flight due to the demand of being very lightweight and in return less durable. In 1996 Ulm, a town in Germany, held a competition with the goal of semi-solar flight. The Icare 2 won this competition as being able to stay aloft with half of the energy being used was solar power.

The Solar Challenger was in 1981 the first which flew from France to England solely on solar power. With the success of the Solar Challenger, NASA started with its own project called HALE (High Altitude Long Endurance). NASA explored the limits of what was possible, which resulted in the HELIOS being able to fly on an altitude over 29km for over 40 minutes. A second goal of the HELIOS, flying for more than 24 hours, was not achieved because it crashed when it encountered heavy winds during a test flight. The HELIOS passed the limit of structural endurance in exchange for weight savings, which resulted in the plane being folded.

In Europe, projects like Helinet, Zephyr and Mercator showed advancements in HALE UAV's with, in 2007, achieving flight duration of more than 54 hours and in 2010 the Zephyr flew for 14 days. The SenseSoar UAV showed its capabilities to fly for more than 24 hours and was a steppingstone for the AtlantikSoar, which is going to attempt to cross the Atlantic Ocean in June 2014 and thus showing that eternal flight on solar power is possible.

Solar Power

How does solar power work? Light is emitted by the sun (or any other light source) and is collected by a solar panel. Light exists of photons, which when in contact with a solar panel, excites the electrons in the valence band. These electrons then jump to the conduction band, become free and electricity is created. This electricity can be used to power multiple devices, from charging your mobile phone to the International Space Station. It also can be used to power planes. When light falls on the solar panels, the power generated can be used for the motors so the plane can fly and to power the flight electronics. Additional available power can be stored in batteries for when times with less light.

As photovoltaic cells have a non-linear output efficiency which is dependent of the solar irradiation, total resistance and temperature, powering the plane directly from the panels would be problematic for the onboard electronics as the power changes multiple times per second. To get a clean voltage from a solar panel, a MPPT (Maximum Power Point Tracker) has to be installed. A MPPT is able to obtain maximum power for any given environment by sampling the output and applying the proper resistance (Figure 2).

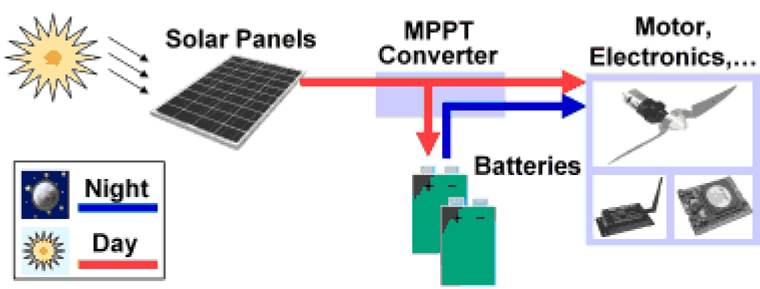


**Figure 2 Solar power schematic (Noth, 2008)**

The total solar irradiance (TSI) is the amount of radiative energy received by Earth from the sun (Willson, 2007). Average TSI between 1986 and 1996 was 1365 W/m$^2$. Not all solar irradiance reaches the surface of the earth. Earth's atmosphere adsorbs much of the irradiance, as do clouds. In 2009, a study by Deneke, Feijt and Roebeling showed estimations of surface solar irradiance in The Netherlands derived from METEOSAT. Figure 3 shows average horizontal surface solar irradiation for 2004 and 2005 for The Netherlands. Figure 4 shows the average horizontal solar irradiance for Europe from 2004 till 2010. These figures show that, on average, a solar radiance of 1000kWh/m$^2$ is available, with higher values during summer and lower in winter. So the average solar irradiance in The Netherlands is 114W/m$^2$ (Velds, 1989). In the Bilt, near Utrecht, the average solar irradiation is shown in Table 1. This table shows that the maximum of solar irradiation is above 500W/m$^2$ in the summer and in the winter 100W/m$^2$ is barely reached.

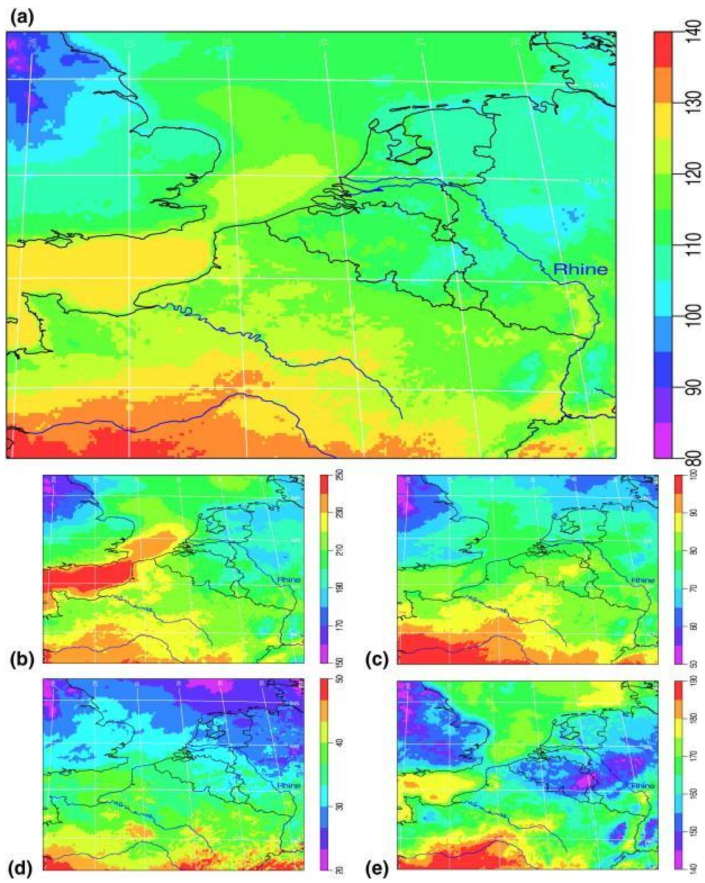


**Figure 3Surface solar irradiance obtained by the SICCS retrieval [in W/m$^2$]. Black and blue lines show country borders and rivers. (a) Annual average (June 2004–May 2005). Seasonal average for summer (b, June–August 2004), fall (c, September–November 2004), winter (d, December 2004–February 2005), and spring (e, March–May 2005), respectively (Deneke, 2008).**

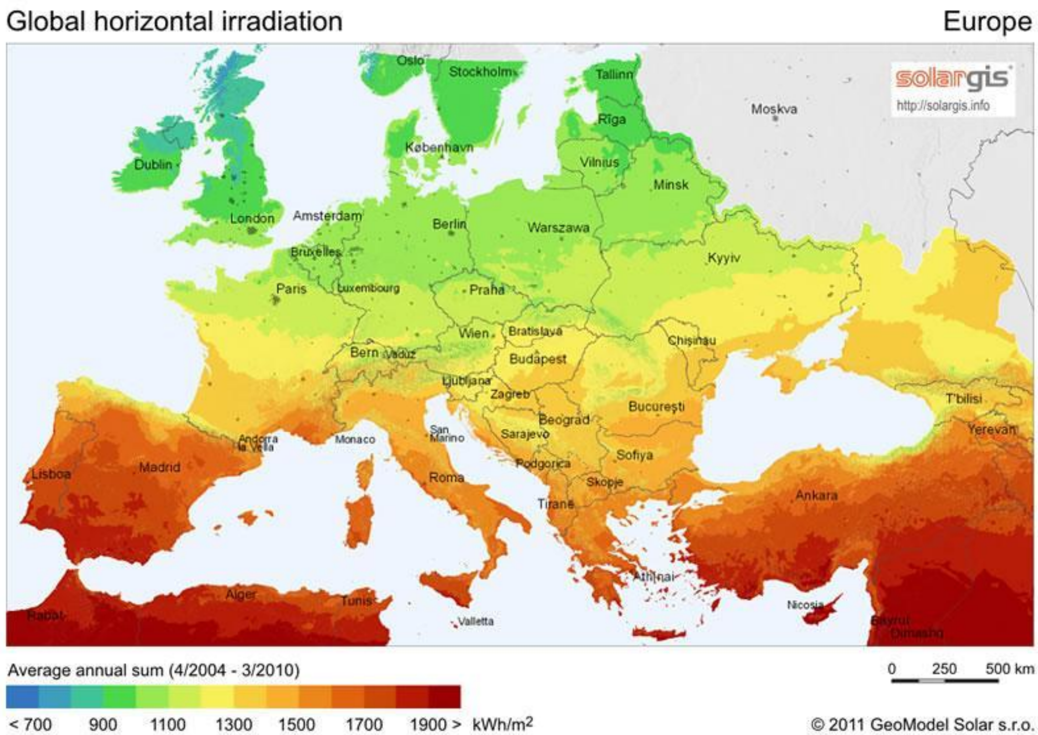


**Figure 4 Average horizontal irradiation in Europe (SolarGIS 2011)**

| hour | jan | feb | march | apr | may | june | july | aug | sep | oct | nov | dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | | | | | | 3 | | | | | | |
| 5 | | | | 3 | 28 | 47 | 31 | 6 | | | | |
| 6 | | | | 36 | 103 | 119 | 100 | 56 | 11 | | | |
| 7 | | | 28 | 119 | 203 | 211 | 189 | 147 | 78 | 17 | | |
| 8 | | 22 | 97 | 217 | 303 | 311 | 289 | 256 | 167 | 78 | 17 | |
| 9 | 28 | 86 | 178 | 311 | 397 | 400 | 375 | 342 | 256 | 156 | 64 | 22 |
| 10 | 72 | 150 | 250 | 386 | 469 | 461 | 444 | 433 | 325 | 222 | 111 | 64 |
| 11 | 108 | 206 | 303 | 433 | 511 | 506 | 486 | 483 | 367 | 264 | 144 | 97 |
| 12 | 125 | 228 | 319 | 447 | 517 | 531 | 519 | 503 | 389 | 275 | 150 | 108 |
| 13 | 122 | 228 | 306 | 439 | 500 | 522 | 511 | 489 | 369 | 256 | 133 | 97 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | 97 | 192 | 272 | 397 | 453 | 489 | 481 | 436 | 333 | 211 | 100 | 69 |
| 15 | 56 | 136 | 222 | 333 | 397 | 431 | 428 | 372 | 264 | 144 | 56 | 31 |
| 16 | 14 | 72 | 144 | 253 | 314 | 350 | 350 | 292 | 181 | 72 | 11 | |
| 17 | | 14 | 69 | 158 | 219 | 261 | 258 | 200 | 94 | 14 | | |
| 18 | | | 11 | 69 | 125 | 167 | 161 | 100 | 22 | | | |
| 19 | | | | 8 | 44 | 81 | 72 | 28 | | | | |
| 20 | | | | | 3 | 17 | 14 | | | | | |
| | | | | | | | | | | | | |
| Total W/m$^2$ | 622 | 1334 | 2199 | 3609 | 4586 | 4907 | 4708 | 4143 | 2856 | 1709 | 786 | 488 |
| Average W/m$^2$ | 77,75 | 133,4 | 183,25 | 240,6 | 286,63 | 288,64 | 294,25 | 276,2 | 219,69 | 155,36 | 87,33 | 69,71 |

**Table 2 Hourly average horizontal irradiance in The Bilt, The Netherlands, in W/m$^2$ (Velds, 1989)**

Solar cell techniques

There are many different techniques available to gather the power of the sun. The first which comes to mind when designing a solar powered UAV is a thin film solar cell. The benefit of thin film cells is that it is just a film which you can put on the wings. They are very thin, thus won't influence the airflow around the wing much, and are lightweight. When looking at the efficiency chart of the NREL (National Renewable Energy Laboratory, Figure 5) one can see that those cells have a maximum efficiency of 20.4%.Other thin solar cells are for instance the double junction cells made by Alta Devices, which achieve an efficiency of 30.8% (Alta Devices, 2013). Weighing at only 180mg per cell (50x20mm and 110µm thick) this looks promising. With the double junction cells from Alta Devices it is possible to get 308 W/m$^2$ in test conditions. In The Netherlands, with a solar irradiance maximum of 531 W/m$^2$ (Velds, 1989), 161.4 W/m$^2$ would be available for flight.

Higher efficiencies are achieved by multi-junction cells. Multi-junction cells are capable of 44% efficiency. These cells are used in space on satellites so they have to be very durable. Increasing efforts are made to make these cells thinner (King, 2006). Thinner cells mean less material needed which result in lower cost to produce them. With these cells 233.64 W/m$^2$ would be available at most in The Netherlands.

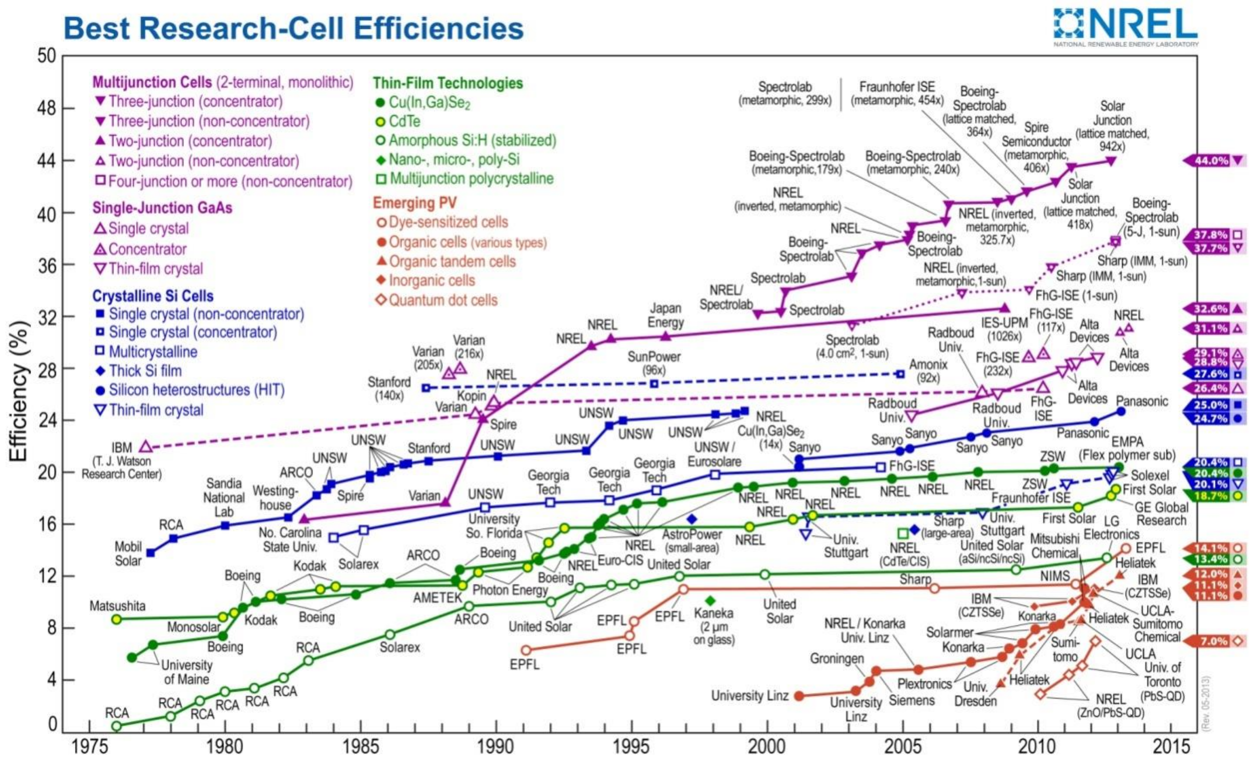


**Figure 5 Best Research-Cell Efficiencies (NREL, 2013)**

# 3. UAV's

In this chapter a study towards a design concept is done for the solar powered UAV. First a fewexamples are given which show that already UAV's are used in a wide variety of fields. Next will be explained why a UAV is usable for measuring air quality. At the end of this chapter a few guidelines will be given for the design of a solar powered UAV.

## Using a UAV

That UAV's are used to track down (and kill) "terrorists" in Afghanistan is a well-known secret. However,that the no-war related use of UAV's is already big business, and that its use is still increasing, is less known. According to Wikipedia, a UAV is an aircraft without a human pilot on board and its flight is controlled either autonomously by computers in the vehicle or under remote control of a pilot on the ground or in another vehicle (Wikipedia, 2013). So the 300 unmanned RMAX helicopters Yamaha Motors sells every year are an example of UAV's. These UAV's are being used for crop spraying on private land (Stafford, 2007).The model airplanes ConservationDrones.org uses for wildlife protection are UAV's. Even the toy-multicopters from manufacturers like Walkera and Parrot are UAV's. The tagline "Now everyone can drone!" from CondervationDrones.org is true. For less than $50 you can have a toy heli/multicopter to play with, some even have a camera onboard. Widespread use of UAV's is not happening yet, mainly because it's a relatively new technology. It was not until 2005 when the world's first fully autonomous UAV, the Steadycopter, took flight. In "Intuitive 3D Maps for MAV Terrain Exploration and Obstacle Avoidance" Stephan Weiss shows that it is possible for a UAV to manoeuvre autonomously through a terrain with real-time terrain-mapping (2011). This real-time mapping is done at the ground station and flight instructions are sent back to the UAV as a lot of computational time is needed. Eresen showed that it is possible to use only a small amount of computational time, so that these computation can be done on-board the UAV and thus fly completely autonomous (2012). The flight pattern is based on visual analyzation of the terrain and a pre-determined destination. Sanahuja developed in 2013 an embedded laser vision system which was capable of indoor autonomous navigation (Sanahuja, 2013). With the widespread availability of UAV's in different sizes and forms, they can also be used for air quality measurements. A big UAV capable of flying with a payload of 10kg is cheaper and less polluting then a normal plane. A big UAV (which flies on fuel) uses 1.65kg fuel for every 100km flown while a Cessna Skylane 15.20kg uses (Barnard Microsystems, 2012).

## Using research UAV's

Haitao Xiang developed in 2011 a low-cost agricultural remote sensing system based on an autonomous UAV (Xiang, 2011). It used a multi-spectral camera to monitor turf grass glyphosate application and showed a usages-possibility for unmanned autonomous aircrafts. In case of a nuclear disaster, like the one with Fukushima after the tsunami of 2011, sending people to measure radiation levels is dangerous for those people. Measuring the fallout cloud also has its difficulties. Measuring it from a plane can be done, but only from a distance and for a limited time. Smidl proposed a system which was capable of following the cloud of pollutants with a UAV that used an unsupervised algorithm which navigated the UAV (2013). One UAV was a complement to the existing ground-based stationary measuring network. Smidl also showed that when using two UAV's simultaneously, the results were comparable with a stationary network of more than thirty sensors (Figure 6).

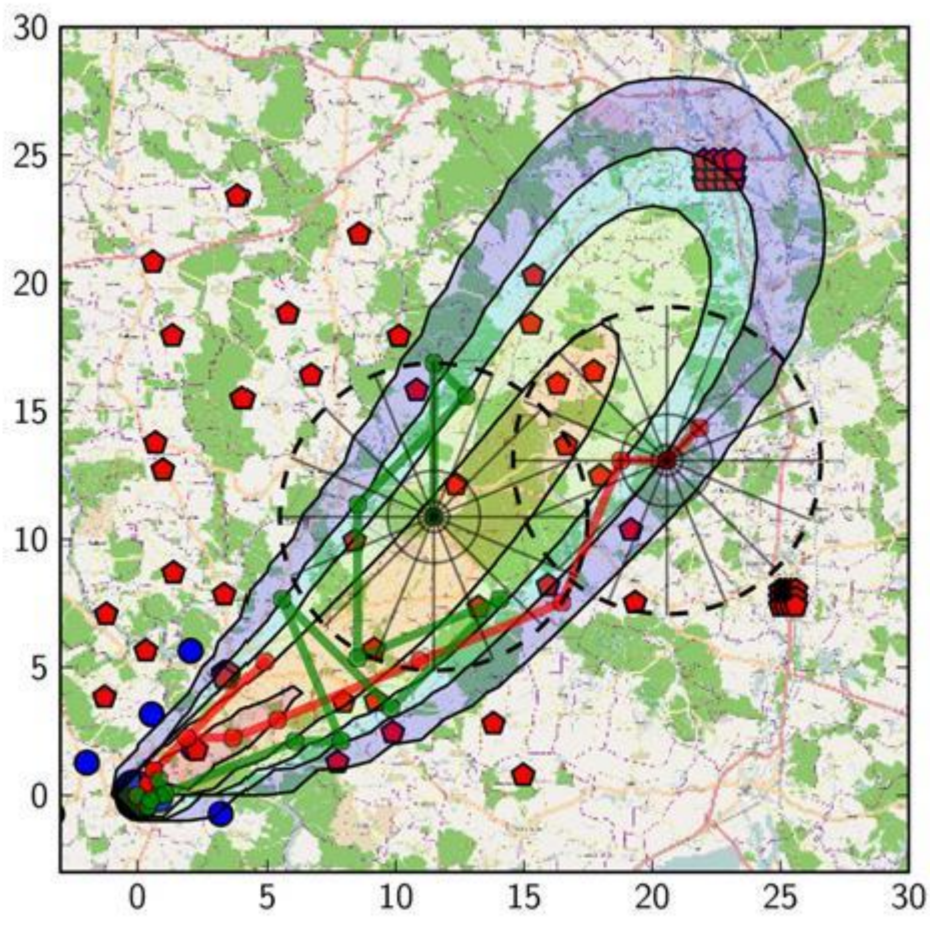


**Figure 6 Combining groundstation network and two UAV's to track a pollution cloud.**

Most of the air pollution is in the boundary layer. The main height of measuring would therefore be in the boundary layer, which is located roughly between ground level and 400m above depending on the location. There is only one location in The Netherlands where the complete boundary layer is researched, and that's at the Cabauw-tower. Research showed there that for instance, during the evening, wind speed at ground level went down but above the boundary layer it increased (KNMI 2009). Chapter two showed different measuring systems. One of the few major projects on air quality in the boundary layer is the PEGASUS-project which uses a zeppelin. The benefit of a zeppelin is that it can move in 3d, instead of the 2d movement of a truck and no movement of fixed ground stations. Another benefit is that it needs little energy to stay in the air as it uses helium to float. Most of the power used is to change direction. The downside is that a zeppelin is expensive, big and not very agile. As Smidl found that two UAV's were capable to get the same results as thirty ground stations, with two zeppelins that would also be possible but then you also need two hangars. A small UAV only needs a few meters of landing space and a small garage as hangar. The only problem of a small UAV is that it is capable of carrying only a small payload (0,5-1 kg). With commercial MPPT's weighing at least 500 gram and air sensors 600 gram, those are the key factors which will provide the feasibility of a solar powered UAV. When able to reduce those weights, air quality measurements in the boundary layer can be done from dawn till dusk. Using field-effect transistors it is possible to measure air quality with a small, lightweight sensor (Andringa, 2013). Mictronics (mictronics.de) designed a small MPPT capable of handling 2 ampere. Noth designed a MPPT for his Sky-Sailor project which weighs 25,86 gram and is capable of handling a power up to 100W which results in a power to weight ratio of 3,87 kW/kg. The MPPT used in the AcPropulsionSolong was capable of 300W at a weight of 100 gram (Noth, 2008). Noth found that the mass of a MPPT is proportional to the maximum power: an average of 3kW/kg. MPPT's from Mictronics and Noth can be seen in appendix A.

## UAV design proposal

The goal of the solar powered UAV is to stay in the air from dawn till dusk at a height of maximum 400 meters and to be operated and carried by one person. SenseSoar proved that solar powered flight is possible for more than 24 hours when relying on thermals and slowly gliding towards earth during the night and ascending on solar power during the day. The UAV of this paper has to stay in the boundary layer, so it can use thermals to stay in the air but it can't glide long during the night as it flies relatively low. Stacking the plane with batteries would be an option to extend the flight time, but the added weight might actually result in less flight time.

When designing an airplane, many factors have to be taken into account. The main part is the wing. The most efficient airplane, from a solar panel view, would be a "nür-flugel" (wing-only)plane. One wing-only design is wat was done with the HELIOS-project, but that wing lacks rigidity/structural strength. The other wing-only design would be like a B2-bomber, a triangle-shaped airplane (flying wing). The problem with a flying wing is its instability, which can be countered with wingtips. Howeverthese wingtips induce drag and therefore reduce the efficiency of the flying wing. Those wingtips also cast a shadow on the solar panels which reduces output. Furthermore in a flying wing there is not much space for electronics.

Thereforea normal shaped plane is preferable. The most efficient planes, in the sense of staying in the air, are sailplanes. A motorglider is preferable for this project due to being independent of thermals. The next step is determining the total weight of the plane, which is done in Table 3.

| **Part** | **Name** | **Number** | **Total Weight parts** |
|---|---|---|---|
| Solarcells | AltaDevices 24.2% | 764 | 137,52 |
| MPPT | self-designed/Noth- | 1 | 26 |
| Airsensor | Field-effect sensor | 1 | 10 |
| Motor | | 1 | 60 |
| RC-receiver | ImmersionRC | 1 | 22 |
| Video-transmitter | ImmersionRC | 1 | 18 |
| Antenna | Spironet | 1 | 8 |
| Servo's | Hitec HS-65MG | 4 | 60 |
| fpv-camera | Wide angle Micro | 1 | 5 |
| UAV-system | ArduPilot Mega 2.5 | 1 | 30 |
| Step-up | ImmersionRC step- | 1 | 2 |
| LC-filter | | 1 | 5 |
| ESC | Turnigy Plush 25A | 1 | 22 |
| Battery | Zippy Compact | 1 | 354 |
| Cables | | ~ | ? |
| Airplane | | 1 | 1000 |
| Extra weight margin | | | 200 |
| | | | |
| Total weight (gram) | | | 1959,52 |

**Table 3 Weight estimation proposed UAV**

With an estimated weight of 2 kilogram the power needed to fly this plane can be determined. In the world of model planes the following guidelines are used:

- 50 W/kg = minimum for level flight, with a reasonably clean plane.
- 100 W/kg = Trainer/Casual/scale flying
- 150 W/kg = Sport flying and sport aerobatics
- 200 W/kg = aggressive aerobatics and mild 3D, effortless loops from level flight.
- 300 W/kg = all out performance (or reasonable 3D).
- 400 W/kg = Unlimited high-speed vertical flight.

50W/kg is the bare minimum for level flight which means that for a 2000gram plane at least 100W is needed. As only specific data on the 24.2% solar cells from AltaDevices was available, the following calculation is done with these cells in mind.

100W from cells which deliver 220mW=0.220W, so 100/0.220=455 cells are needed. One cell measures 50x19.6mm and has a surface of 0.00098$m^2$. Total surface needed for the solar panels is 455x0.00098m2=0.4459$m^2$. Henk Tennekes found that a fruit fly and a Boeing 747 have the same weight (W in Newton) to wing area (S in $m^2$) ratio: $W/S=47W^{(1/3)}$ (2009). With a weight of 2kg=20N the wing area needed for unaccelerated level flight is 0.157$m^2$. With a wing area of 0.446m$^2$ needed for the solar panels, more than enough wingsurface is available for flight. Figure 7 shows the relationship between total mass and the wingspan.

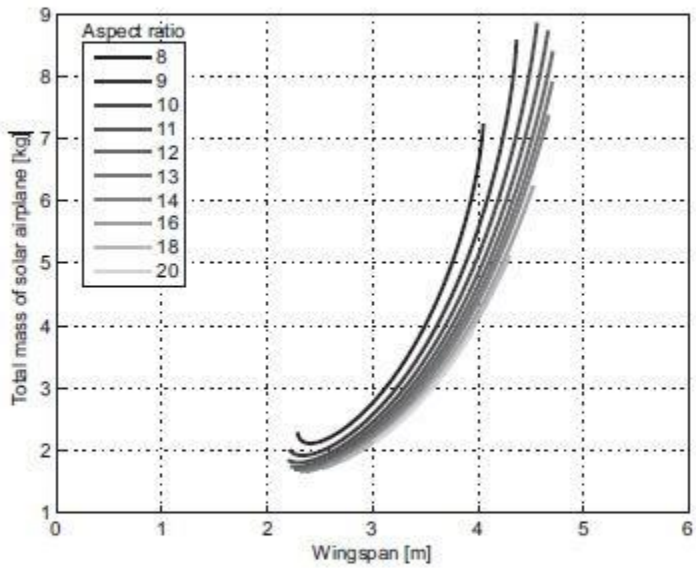


**Figure 7 Relationship total mass (kg) and wingspan (m) (Noth, 2008)**

For an airplane with a total mass of 2 kg a wingspan of 2.5-2.75m is needed for continuous flight. Solar irradiance in the summer was more than 500W/m$^2$ and with 24.2% efficient solar cells 121W is then available for flight. An irradiance of 413W/m2 is needed for flight on solar power only, which is available from April through August. With the 30.8% efficient cells from Alta Devices an irradiance of 325W/m2 is needed, which is available from April through September. When using multi-junction cells with an efficiency of 44%, 227.3 W/m$^2$ solar irradiance is the bare minimum what has to be available to be able to fly. These values are around noon from February until October and from April until August continuous flight is possible from 8am till 5pm.

## 4. Discussion/Conclusion

This thesis discussed the possibility of using solar powered UAV's as a means of measuring air quality. As Smidl has shown it is possible to use a UAV in case of a single source of pollution in addition to existing ground-stations. Two UAV's can achieve the same quality measurement data as 30 ground-stations. However those UAV's cannot stay airborne forever while ground-stations can measure day and night. Geo-stationary satellites can observe the same spot continuously but are inaccurate when clouds are blocking the view. Airborne measurements conducted by weather balloons only create a vertical profile whereas airplanes and zeppelins can give 3d profile of the pollution but are more expensive then a small UAV.

This thesis also presented a guideline which can help with designing (and making) a solar powered UAV capable of doing air quality measurements in the boundary layer. It has the advantage to measure everywhere as long as the sun shines. With increasing miniaturization of electronics better sensors can be put on this UAV. Advancements in photovoltaic techniques will ensure that the UAV also flies in the winter or less clear skies. As shown in chapter 3, flight on solar power is only possible around noon for the months April until September and in June it is possible (with the 24.2% cells) to fly solely on solar power from 9am till 3pm.The 30.8% cells can achieve a continuous flight from 8am till 5pm in June. Further advances in solar cell efficiencies can make year round flying on solar power possible. Flying from dawn till dusk is not possible solely on solar power, the irradiance of the sun is just too low for flight. With the use of batteries flight can be extended so that a flight from dawn till dusk becomes possible and with better batteries day and night flight on a fixed altitude might eventually be possible.

A UAV can be a cheaper and less polluting alternative for airplanes, weather balloons and zeppelins in case of (sudden) single-point pollution but its flight time is the limiting factor. A UAV can also be made smaller and lighter so the availability of a runway is not an issue when operating it. When solar cells are added it can be an autonomous airborne measuring device during day-time and be a good addition to existing measurement stations.

# 5. Acknowledgement

Writing a thesis in less than 10 weeks was a nice challenge and I could not have done it without the help of a few people.

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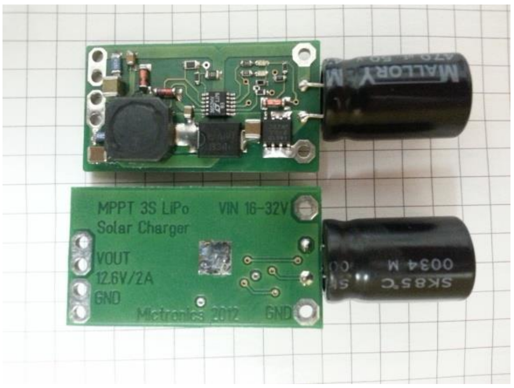
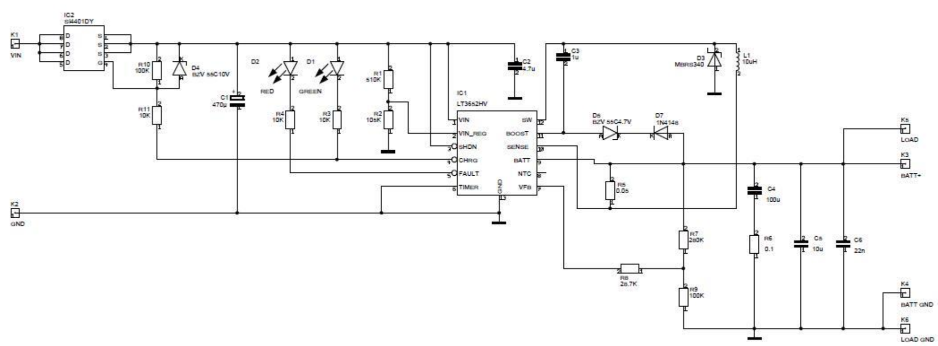
Last, but not least, I would like to thank my father for his assistance in understanding the electronics part of a solar powered UAV and for his guidance and review of my thesis.

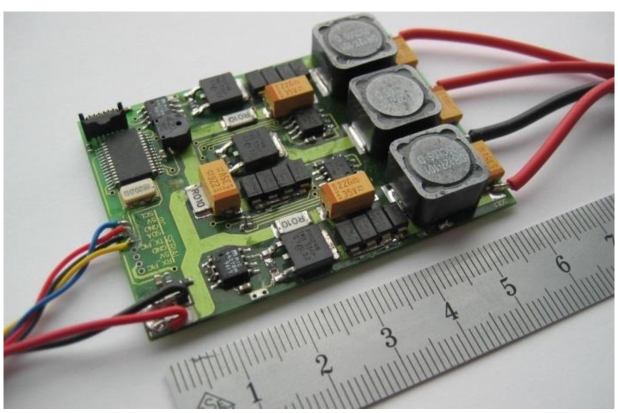
# A.Two MPPT’s with schematics

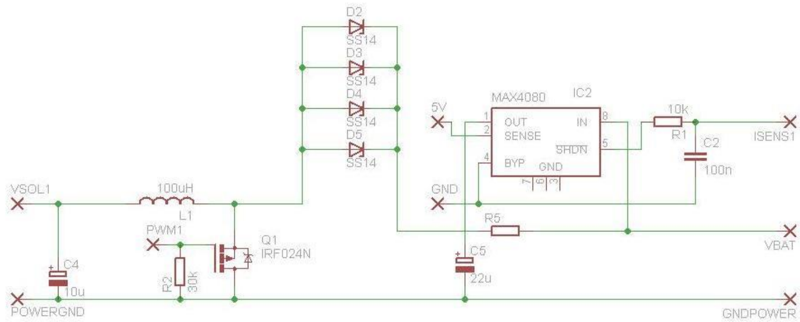
Mictronics:



Sky Sailor:




D2
SS14
D3
SS14
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D5
SS14
MAX4080
IC2
5V
OUT
SENSE
IN
SHDN
BYP
GND
10k
R1
C2
100n
ISENS1
GND
VSOL1
100uH
L1
R5
VBAT
PWM1
Q1
IRF024N
C5
22u
C4
10u
R2
30k
POWERGND
GNDPOWER

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