Geo-information Science and Remote Sensing

Thesis Report GIRS-2018-55

EVALUATION OF AN NO_2 SENSOR MOUNTED TO A UAV FOR MEASURING AIR POLLUTION.

Imke de Man

November 12, 2018

WAGENINGEN
UNIVERSITY & RESEARCH

Evaluation of an NO_2 sensor mounted to a UAV for measuring air pollution.

Imke de Man

Registration number 95 04 22 541 120

Supervisors:

João Valente
Qijun Jiang

A thesis submitted in partial fulfillment of the degree of Master of Science
at Wageningen University and Research Centre,
The Netherlands.

November 12, 2018
Wageningen, The Netherlands

Thesis code number: GRS-80436
Thesis Report: GIRS-2018-55
Wageningen University and Research Centre
Laboratory of Geo-Information Science and Remote Sensing

Disclaimer

This report is written by a student of Wageningen University as part of a masters programme and is executed under supervision of the Laboratory of Geo-information and Remote Sensing. This report is not an official publication of Wageningen University or Wageningen UR. The content of this report is not the opinion of Wageningen University or Wageningen UR.

Use of information from this report is for own risk and it is advised to check this independently before the information is used.

Wageningen University is never liable for the consequences that result from use of information from this report.

Laboratory of Geo-Information and Remote Sensing

Wageningen University

Postbus 47

6700 AA WAGENINGEN

T: +31 (0)317 - 481834 / +31 (0)317- 481878

Abstract

This research investigates the possibility of monitoring air quality, more specifically NO_2 emission plumes, with the use of an electro-chemical sensor mounted to an Unmanned Aerial Vehicle (UAV). The combination of an electro-chemical sensor and the UAV has been touched upon several times in literature, but is never experimented with in an outside situation. The aim of this research is to evaluate if this sensor mounted to a UAV is of good use in a real-life outside situation. Therefore first it is evaluated what was done before in literature. Next the system is tested outside in a real-life outdoor situation: it measured the emission of a tractor on two different days, with two different flight patterns, the zigzag pattern and the spiral pattern, on a height from 3m to 7m. Both days had a different wind speed. From the literature study it showed that more research can be conducted to the ideal sensor location on the UAV and the literature study showed that calibration of the sensors to correct for temperature and humidity is important. This calibration is experimented with in laboratory calibration as well as outside calibration. From the experiments it showed that wind has a significant effect on the measurements. The first day the wind speed was between the 0.0 m/s and 2.9 m/s, which resulted in a percentage of measurements measured above the background concentration (percentage M.A.B.) from 73.0% to 99.5%, while the second day with wind speeds between 2.1 m/s and 5.3 m/s had a result of 4.8% to 14.1%. The height of measuring and the influence of flight pattern had no significant effect on the percentage M.A.B. Therefore this research concludes that for the use of an NO_2 sensor mounted to a UAV wind should be strongly taken into consideration. This effect of wind on gas plumes needs to be taken into account in the future by measuring gas on days with a low wind or by finding flight patterns that can deal with high wind speeds.

Keywords: *UAV, electro-chemical gas sensor, air pollution, mobile sensor, NO_2 detection, Unmanned Aerial Vehicle, wind effect*

Contents

Chapter 1

Introduction

The topic of this research is the evaluation of the use of an electro-chemical sensor measuring NO_2 mounted on a Unmanned Aerial Vehicle (UAV). The gas NO_2 is a gas which is released through combustion engines, polluting the air. By measuring the emission with a UAV, more can be learned on the spread of the gas.

1.1 Background and context

NO_2 is a gas which is indicative for air pollution and therefore interesting to research in the context of measuring air pollution. NO_2 is a harmful gas for public health and the environment. Mapping the amount of harmful gasses in the air and mapping where the gasses are located will in the end help for improved policies and behaviour, which will improve the air quality.

1.1.1 Air Pollution

Worldwide air pollution is a large problem, as the World Health Organization (WHO) states: 'More than 80% of people living in urban areas, which monitor air pollution, are exposed to air quality levels that exceed the World Health Organization limits' (WHO, 2016). In the middle of the 20^{th} century methods were invented to analyze the relation between air pollution and mortality. From this point on statistics were created which showed the severe issue of air pollution for the public health. Having these statistics created the possibility to do research on maximum concentrations of toxic elements in the air (Anderson, 2009). The WHO creates guidelines on air quality for countries, based on these types of researches (WHO, 2017, 2006). The existence of these guidelines does not mean that the Air Quality is met everywhere. Different pollutants cause the decrease of air quality. Although air quality is improving in densely populated and dense traffic areas the air quality is often still not sufficient for a healthy living environment (Mijling et al., 2018).

1.1.2 Spatial Resolution In Measuring

The severity of air pollution is continuously measured. Several countries and large cities have a continuously measuring system. For example, in the Netherlands there is a measurement system which has static sensors distributed among the Netherlands on places with highways and/or industry (Luchtmeetnet, 2017). The results are visible for everyone on the luchtmeetnet website: https://www.luchtmeetnet.nl/. Also for example Paris or within the United States have such measurement systems (Cox and Blaszczak, 1999; Airparif, 2017). These measurement systems show over time a large dataset with a large amount of temporal data, which shows trends over the years. This data gives as well insight on the days which have higher air pollution than other days. For example with low wind speed and high moisture there is more air pollution (FMI, 2018). These insights are very useful, but sometimes still not enough. The Dutch government estimates once a year the total emission per location in the Netherlands over a year time. This research is for a large part done with calculations with data about the amount of fuel sold, together with weather data and result in an emission map with a resolution of 1km by 1km. This research led to unexpected lower air pollution for the harbour of Rotterdam. Therefore a more precise research was done, with more locations where the air pollution is measured. This more spatially precise research gave higher emission values (Klein and Fortuin, 2014; RIVM, 2017). This is an example how in air pollution at this moment the temporal resolution is quite high and gives good insight, but the spatial resolution can be more precise. Increasing the spatial resolution gives new insight which precise areas are more prone to air-pollution and need more attention.

Next to that, most of the data is presented as 2D information. Air pollution is approached as a flat phenomena. For example the new European satellite, TEMIS, measures air pollution in the Troposphere and creates a distribution image with 10^{15} molecules per cm^3 (KNMI et al., 2017). This information is very useful to understand the spread of air pollution over the globe. Risk areas can be pointed out and also the influence of for example mountains can be understood better. When this risk is known it is interesting to look in more details to these areas. These areas with more air pollution have higher risks for public health and also nature areas can get affected by air pollution (Anderson, 2009). More spatially precise as TEMIS is the earlier mentioned Luchtmeetnet (2017), and more precise as Luchtmeetnet is the research conducted in the Rotterdam harbour. All these 3 examples are measured as 2D information. To have a better understanding of air pollution a third dimension: altitude can be of interest (Weber et al., 2017).

1.1.3 Mobile Measuring

A development in the area of air pollution measurement, is the development of mobile measuring. The mobile measuring technique is upcoming as an answer on the temporal rich, but not spatially precise data (Riley et al., 2016). Air pollution is measured at fixed locations. To create a map for an area which is for example covering the Netherlands, the areas between the fixed point are calculated with regression statistics (Riley et al., 2016). UAV stands for Unmanned Aerial Vehicle. This means that a vehicle is flying which is being directed from the ground. The basic idea is developed in army context and exists already since 1880, since Australia created an unmanned balloon, which was able to carry a bomb. This developed further the last couple of decades until the UAV we know now. Since 1990 the UAV is getting more into the commercial market, with a peak the last couple of years. This growth in development of UAVs makes sure the technique is more widely available and can also be used within science (Fahlstrom and Gleason, 2012). For example, because this type of mobile measurements is done as a cheap, fast and flexible method in comparison with for example measurements done on an helicopter or airplane, as is done in air pollution research unto now (Kurtenbach et al., 2016; Berg et al., 2012; Weber et al., 2017). Another advantage of this type of mobile measurement is that it can easily measure in height. Together this mobile type of measurement gives a higher spatial resolution. This option for increasing the resolution in altitude is researched more within this research.

1.1.4 Pollution Sources

Different pollutants cause the decrease of air quality. For public health the main pollutants are: Particulate Matter (PM), carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) (WHO, 2016). In pollution sources research a distinction is made between primary sources and secondary sources. As primary source NO_2 is a good example. NO_2 is directly emitted from engine combustion. A good example of a primary source is O_3, because when NO_2 reacts with ultraviolet light, it become O_3. O_3 is one of the main components of smog. Because NO_2 indirectly causes another pollutant it is an interesting pollutant for research (Friedlander, 1973; WHO, 2016).

Air pollution is mainly measured in cities, where a high density of people is living together. These people are living next to highways with lots of transport and areas with a lot of industry. Transport as well as industry are examples of the cause of air pollution, man-made sources of combustion engines. To reduce the pressure of the highways with transport, the EU actively promotes to have more use of ships on the rivers. In the White Papers (EuropeanCommission, 2011) the European Union expressed the wish for more inland navigation. More goods can be transported at once and next to that the NO_2 emission is lower of ships than of trucks per kilogram of goods transported. This seems as a good solution to improve the air quality in densely populated areas. Only, this has a risk of a shift of lower air quality to other parts of the country. Now the lower air quality is mainly concentrated on built-up and industrial areas. While inland navigation is transport over rivers, this will not only pass by built-up areas, but also nature areas and smaller cities and villages. Therefore new types of areas needs to be measured. Not only the areas which are built-up and densely populated, but also the nature areas. Having higher air pollution in nature areas has a negative effect on nature as well as for the people using the nature for recreational activities (Breuninger et al., 2012; Stella et al., 2013). For the nature the NO_2 can damage the membrane of the plants. As result the plant cannot function as good as before and will after too long exposure to NO_2 die (Eller and Sparks, 2006). Taking this effect into consideration, it is interesting to know what the effect is on the air pollution in nature areas due to possible increase of traffic on the rivers. Especially the height and spread of the emission plume can be of interest in this case. If the plume is emitted in such a high altitude it is possible that the direct nature is not affected, but a nature part further away (Kurtenbach et al., 2016). Therefore it is interesting to add to this local measurement system a 3rd dimension: measuring in altitude (Villa et al., 2016b). This inland navigation change is an example in which new measurements techniques, which measure as well in altitude, can be used. Later on adding this dimension is not only interesting for inland navigation, but can also show the distribution of other emission sources, such as factories or traffic.

1.1.5 Developing a New Technique

The insight of the wish of measuring on more locations than the city, combines a couple things. First of all, in the Netherlands the main sensors are placed in the densely populated area and in industrial areas (Luchtmeetnet, 2017). Taking again the example of inland navigation, the sensors need to be placed in harder to reach area, because due to dense nature close to the rivers or it is hard to place for example a sensor in the middle above the river. Therefore measuring air pollution requires the testing of new methodologies to determine the air quality, quick, flexible on multiple locations and on hard to reach locations.

Within this context it can be interesting to study the use of the mobile measurement system: the UAV. A UAV has a high spatial resolution within 3 dimensions. So it is possible to research the plume of NO_2 emitted by a hard to reach source such as inland navigation and the spread of this plume over the area. Understanding this behaviour gives insight in how the nature will be affected and where in the area the air pollution will concentrate.

Research on measuring air pollution with a UAV in 3 dimensions is done before. Such as Weber et al. (2017) who did research to Ultra Fine particles air pollution around a traffic dense bridge in Düsseldorf. The sensor used in this research was an optical particle counter, which works with a small laser beam. The main founding of this research was that the Ultra Fine particle plume concentration could not be detected anymore after 35m of height. So this indicates that there is a higher health risk in 35m above the high way. Also Peng et al. (2015) researched the air pollution with an UAV. The focus was to gain knowledge on the vertical distribution of Particulate Matter with a diameter of 2.5 micrometre. The PM2.5 was measured in the air layer from 300m up to 1000m. The PM is detected with a Sidepak Aerosol Monitor, which is a laser photometer. Also Berman et al. (2012) used sensors on an UAV to measure air pollution. This research focuses mainly on CO_2, CH_4 and H_2O. The main motivation for using an UAV is to get a higher spatial resolution than a satellite can offer. This study found it successful to access this way remote areas and measure the concentration greenhouse gases.

The research measuring air pollution with an UAV is often done with a spectrometer. Although in air pollution research this is not the only type of sensor used. For example Jiang et al. (2016) did research on developing an electro-chemical sensor for measuring the air pollutant NO_2 within a city context. This developing was done with citizen science. The aim within this research was to develop a low-cost sensor which could be made by citizens, this way more air pollution data could be gathered. NO_2 as air pollutant was chosen to measure, because it is the pollutant which had the most chance to be higher than legally allowed. The requirement of a sensor which is low-cost is not only interesting for citizens, but is also be of interest for this research. Another advantage is that these sensors are very small and light-weight, which makes it easy to mount on small UAVs and small UAVs can be bought and flown more easily. The requirement in the article resulted in the choice of an electro-chemical sensor: Alphasense NO_2 sensor (NO_2-B42F or NO_2-A42F) (Alphasense, 2017). If such a low-cost sensor in comparison with a spectrometer can be used for measuring air pollution, that will be of use of broader executed air pollution research. Patterson et al. (2005) already used an electro-chemical sensor to detect gases from an active volcano. At that moment the electro-chemical sensor did not show significant results. This sensor was focusing on multiple gasses so with a sensor which focuses on one, it can probably gather more useful results. Villa et al. (2016b) used the Alphasense sensor to measure NO_2, next to 3 other gasses. This research was focused on validating the Alphasense sensor within a closed room. This was successful in measuring closed room, but mentioned is the danger of the effect of wind. Villa et al. (2016b) recommends to further research this application in an outdoor situation. Within this research this will be done.

Taking the above together the advantages of an electro-chemical sensor is that the sensor is cheap, readily available, small and easy to use. The advantages of a UAV is that it can be taken outside easily to the area of interest, a UAV can be small and it provides information in 3 dimensions. Both have the characteristics that they are small, light-weight and easy to use. Therefore this combination seems as a valuable combination. This needs to be researched further. Several researchers made a start, but it is not completely evaluated unto now. This research will evaluate this use in an outdoor situation. Below the research questions and the methodology on how to do this will be explained.

1.2 Problem statement

Research shows that the electro-chemical sensor mounted to the UAV seems as a promising and valuable option for measuring air pollution, but needs more research. Mainly what is missing is an evaluation, which dives into the combination and evaluates if this combination is indeed easy to use and of good use in a real-life outside situation. This research will focus on the evaluation of the use outside. First it will evaluate the combination on its development unto now, to see if improvements need to be made and which improvements it has to be. Next a further look will be given to the calibration of the sensors, because this is an important step for gaining results, and effects the use of the system. Lastly an evaluation will be done on the use of the sensor and UAV combination in a real-life outdoor situation. All these parts together will result in an evaluation if the combination has a promising future and what needs to be done to improve more.

1.3 Research questions & objectives

The objective of this research is to evaluate the use of an electro-chemical NO_2 sensor mounted to a UAV in an outdoor situation. The hypothesis is that the combination will be a valuable and easy-to-use system for gaining insights in the spread of NO_2 emission. To meet this objective of evaluating the measurement system together several questions have to be answered. This resulted in one main question and two sub-questions. These questions will give an overview on the state-of-the-art at this moment in the research on this topic and secondly will evaluate the outside- use of the sensor and UAV combination.

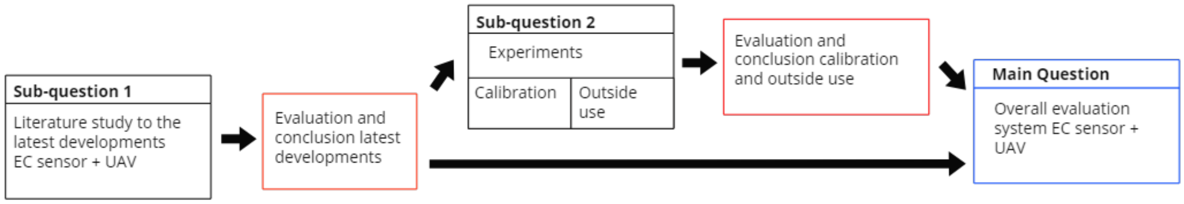


Figure 1.1: The methodology work flow of this research, which will answer the sub-questions and the main question. The outcome of the first sub-question will be used for answering the second sub-question. Both sub-questions will answer the main question.

Main research question. Is it possible to characterize an NO_2 plume with an NO_2 electro-chemical sensor mounted to a UAV?

Sub-questions

a What is known in literature about the development and use on electro-chemical sensor mounted to a UAV?

b What is the influence of wind speed, height of the measurements and flight method on the measured NO_2 with the measurement system?

(1) What is the influence of wind speed on the measured NO_2?

(2) What is the influence of measurement height on the measured NO_2?

(3) What flight method is most suited to find the NO_2 plume?

1.4 Research Outline

In this chapter is explained how the main question and research questions will be answered. The general flow is shown in figure 1.1.

The first sub-question will be answered through a literature study and will be written down in chapter 2. This literature study will show what is known unto now about the use of sensors mounted to a UAV and more specific electro-chemical sensors mounted to a UAV. This chapter first zooms in on the development of a sensor system. When it is understood which sensors are used and which electro-chemical sensor is of good use, the chapter will zoom out and look into the ideal sensor mounting location on the UAV. When more is known about the mounting location the literature study will focus on the calibration of the sensor. At last, the literature study will evaluate the use of the sensor UAV combination, by looking into flight paths which are ideal for plume detection. With this set-up this chapter zooms first in very specific to the sensor and in the end zooms out and will look into the outside use of the sensor UAV combination. This literature study will find characteristics of the UAV as well as characteristics of the sensors, with both each advantages as well as disadvantages. An obvious example is that a UAV needs light-weight sensors and an electro-chemical sensor is light-weight, which makes that the combination matches. It is expected to find more of these characteristics which will or will not match, which together will result in an evaluation of the system. In the conclusion and discussion part of this chapter these characteristics will be discussed.

The second sub-question will be answered with experiments. First the used methodology will be explained in chapter 3. Secondly the results of the experiments will be shown in chapter 4. Thirdly the results of the experiments will be discussed in chapter 5. The calibration part deviates slightly and is completely explained and described in the methodology chapter, as the results have influenced the analysis methodology.

In the last part the UAV with the electro-chemical sensor are used outside. The experiment is executed in the field of Unifarm, which is an open space agricultural field with no blocking objects obstructing the wind flow. The combustion engine was a tractor, which was running stationary at one point as an example NO_2 source. On the plume emitted by the tractor two different flight paths have been tested. The exact experiments are explained in the methodology section of this chapter. With these experiments it is researched if the electro-chemical sensor characteristics meet the characteristics of the UAV as was researched in the literature study from the previous chapter. At the end of this section a conclusion and discussion is given on the experiments outside.

In chapter 6: Conclusion, all chapters will be brought together and the sub-questions and main question will be answered. The last chapter is chapter 7, recommendations, which show the recommendations for further research.

Chapter 2

Literature study: sensor system

As explained in Chapter 1, the objective is to evaluate the use of an electro-chemical sensor mounted to a UAV, an Unmanned Aerial Vehicle. To be able to do this according to already proven methods a literature study has been conducted. The review starts broad with an introduction on gas detection with a UAV as well as with other flying objects such as airplanes and helicopters from which we can learn. Then the review starts and the chapter will first describe the electro-chemical sensor and then slowly zooms out by addressing the following topics: sensor location on the UAV, calibration of the sensor and as last detecting a plume with this system. In the end of the review the characteristics of the system combination will be given and advice on what knowledge is missing at this moment on this topic. Together this will answer the first sub-question: How far is the development and use on electro-chemical sensor mounted to a UAV?

2.1 Introduction to the field of gas detection with a UAV

Using gas sensors on the UAV is an upcoming science, which is used in various fields, from agriculture to finding hazardous situations (Pobkrut et al., 2016; Villa et al., 2016a). Villa et al. (2016a) did a literature research in which 60 articles were analyzed on using UAV systems for Air Quality Monitoring. Many of these researches see air quality monitoring as detecting hazardous plumes of for example volcano eruptions. The systems build for these purposes are large UAV systems which can stand the conditions of monitoring volcano emissions and have a long flight endurance. These UAV systems set-ups make use of large sensors as for example spectrometers (Peng et al., 2015). The article concludes with naming smaller UAVs with smaller sensors such as Villa et al. (2016b); Neumann et al. (2013). Villa et al. (2016a) concludes its article that more research needs to be done to make easy, cheap and light-weight sensors which can be deployed easily on a UAV.

A lot of air quality research is still conducted with airplanes such as Berg et al. (2012); Kim et al. (2009); Nunnermacker et al. (2008). An advantage from using airplane is that its possible to cover very large areas such as Nunnermacker et al. (2008), who covered an area of 35km^2 for their research, in which they found 64 transects of emission plumes, mainly from industry. Disadvantage from this method is the planning. You need expensive materials, in advance time planning and align schedules of airports, pilots and researchers. The next developments have been in the larger UAV systems, such as Khan et al. (2012) developed a Helicopter UAV with sensors and Malaver et al. (2015) developed a fixed wing UAV driven on energy from solar panels and Peng et al. (2015) developed a fixed wing UAV driven on petrol and Berman et al. (2012) used a fixed wing airplane as well. The area Peng et al. (2015) was able to cover was 4km^2 in a time of 2 hours and Berman et al. (2012) covered an area of 6km^2. The main advantage of these systems in comparison with the airplanes is that these UAVs could be launched from the research area location. Next to that, it is easier to learn how to fly a UAV than it is to get your license for flying an

Table 2.1: Sensor types found in literature, together with the device it is mounted to and the literature references. PC stands for Particle Counter, MOX for metal-oxide sensors, EC for electro-chemical sensor and FW stands for Fixed Wing UAV

Sensor type	Device	Literature
Laser based	helicopter uav, airplane, FW (solar)	(Khan et al., 2012; Berg et al., 2012; Berman et al., 2012; Malaver et al., 2015)
PC	hexacopter, octocopter, FW (petrol)	(Villa et al., 2016b; Weber et al., 2017; Peng et al., 2015)
MOX	FW(solar), Quadcopter	(Malaver et al., 2015; Neumann et al., 2016)
EC	Hexacopter, Quadcopter	(Villa et al., 2016b; Pobkrut et al., 2016; Neumann et al., 2013, 2016; Roldán et al., 2015)

airplane. Still with larger UAVs a flight license might be obligatory, which makes it not as broad useful as can be thought. In the Netherlands a UAV is large when it is heavier than 4kg and if the flying area is between 100 to 500meters from the pilot and the UAV is used professionally a flight license is needed. For UAVs lighter than 4kg, and flying in areas upto 100m from the pilot, no license is necessary, only when using the set-up professionally, for this case a light-license can be enough (Rijksoverheid, 2017). This last legislation show already that it can be even more advantageous to use even smaller UAVs. Next to a legislation advantage, some smaller and cheaper UAVs are available. Often a quad-copter, such as used in Pobkrut et al. (2016); Neumann et al. (2013); Villa et al. (2016b); Roldán et al. (2015). Smaller UAV systems with gas sensors have been developed for the use in for example greenhouses. Roldán et al. (2015) for example developed a system which detected CO_2 in a greenhouse.

With the decrease in size of measurement equipment, the sensors needed as well to get smaller. This is visible in the literature as well, in the table 2.1 are the sensor and method combinations visible. The choice of sensor is not only depending of how large system you would like to use, but also what air polluter is researched. All the article named did research on measuring air pollution by measuring in the air, but all measured other polluters. For example what is visible in the table with the particle counter (PC) sensors are mostly researches which focus on measuring PM_x, which stands for particulate matter. PM are small particles in the air, which can be optically detected. Air polluters which are gases, such as CH_4 (methane), CO_2 (carbon dioxide) and NO_x (nitrogen oxide and nitrogen dioxide) can be detected with the laser based systems such as spectrometers, as well as with the MOX sensors and EC sensors.

Especially comparing the laser based sensors with the MOX and EC sensors, a large reduction in size is visible. The laser based sensors are used on a manned airplane such as in the research of Berg et al. (2012). When it is not used in a manned airplane it is used in a a large UAV, such as the Helicopter UAV of Khan et al. (2012) and the Fixed Wing UAV of Malaver et al. (2015). The smallest sensors are the metal-oxide sensors and the electro-chemical sensors. These are on the smaller devices, such as the quadcopter of Pobkrut et al. (2016); Neumann et al. (2013). The main gasses researched are CH_4 (methane) and CO_2, as in Khan et al. (2012); Malaver et al. (2015); Berman et al. (2012); Neumann et al. (2013).

Specific NO_2 detection with a UAV is done with larger sensors, such as the spectrometer. For example the research of Berg et al. (2012) used a spectrometer on an airplane to measure NO_2 emission of a ship. With a smaller system Villa et al. (2016b) made use of an electro-chemical sensor to measure specifically NO_2. Both of these article were experimental and set the first steps in measuring the gas NO_2.

As Villa et al. (2016a) conclude more research can be done to make easy, cheap and light-weight sensors which can be deployed easily on a UAV. So more research can be done within this area. The smaller and cheaper the sensors, the smaller and cheaper the UAV can be, which makes sure that the system can be widely used. Also the fact that NO_2 is not that widely researched as a pollutant to be detected with a UAV can have more research.

2.2 Developing a sensor system

From the literature above it becomes clear that more research can be done on developing a ready, affordable, light weight sensor/UAV combination for NO_2. Below will be explained what needs to be researched more specifically within each topic to create a sensor which is able to measure NO_2 with a UAV.

2.2.1 Flexible & affordable alternatives

Up to now research to NO_2 is done with different sensors. The sensors used differ from laser based sensors and spectrometers (Khan et al., 2012; Berg et al., 2012; Berman et al., 2012) to particle counters (Weber et al., 2017; Peng et al., 2015) to using several combinations of sensors such as infrared and metal-oxide sensors (Malaver et al., 2015), electro-chemical sensor with particle counter (Villa et al., 2016b) and electro-chemical sensor with infrared sensors (Neumann et al., 2013). Focusing on NO_2 mainly the spectrometer is used (Berg et al., 2012) and the electro-chemical sensor as small sensor Villa et al. (2016b). The advantage that the NO_2 electro-chemical sensor is small is a good characteristic to mount it on a UAV.

Reading research which focuses on measuring air pollution with NO_2 as polluter and not specific measuring with UAVs, more often the electro-chemical sensor is used. An example is the research of Jiang (2018). In which with citizen-science multiple sensors were developed, so citizens were able to measure at their location of interest. Therefore the NO_2 sensor needed to be easy to use, affordable and precise enough for measuring differences in a city context. Bhoga and Singh (2007) reviewed the development of several types of electro-chemical gas-sensors. It has a quick response time, it is small, affordable and the development of the sensors continues. Still it has as well a couple downside, such as its cross-sensitivity, influence of temperature and humidity and the noise in the signal as Jiang (2018) has found.

2.2.2 The pollutant Nitrogen Dioxide

Nitrogen dioxide is a gas which is emitted through the burning of fossil fuels. Therefore at this moment the main cause of an overrun of NO_2 is mostly man-caused. The emission sources differ from chimneys of industries to cars to ships. The danger of NO_2 is the gas itself, by causing respiratory problems, but a problem as well is the chemical reaction it causes. NO_2 is a highly reactive gas. It can cause 3 chemical reaction, depending on external factors, such as light (Kim et al., 2009). One, the most known, chemical reaction is when NO_2 reacts with visible light, it forms ozone (O_3) and nitrogen-oxide (NO). Next to ozone is responsible for smog, which effects people their health negatively. This titration process happens fast directly after the emission of the plume and mainly on the borders of the plume. In the middle of the plume, seen in x- and y-axis as well as on the z-axis, the NO_2 holds on the longest (Kim et al., 2009). This all together causes the the negative effect of NO_2 on air pollution

2.2.3 The working of an electro-chemical sensor

An electro-chemical sensors of AlphaSense exists out of 4 electrodes: reference electrode (RE), working electrode (WE), counter electrode (CE) and the auxiliary electrode (AE). These are connected with electrolyte and when the target gas, NO_2, goes through the filter (a membrane), the WE will give a redox reaction, resulting in a current. This will determine how much gas is in the air. For interpreting the results this sensor gives, mainly the WE and the AE are important. The AE is shadowing the working of the WE, only while the WE gives a reaction as soon as it is in contact with the target gas, the AE will not give this reaction. This means that the AE is partly a correction for everything the sensor reacts on which is not the target gas.

Table 2.2: Location of sensors corresponding with sensor type, from the found literature. PC stands for particle counter sensor, MOX for metal-oxide sensor and EC for electro-chemical sensor.

Location on UAV	Sensor Type	Literature
Underneath	Laserbased	(Khan et al., 2012; Berg et al., 2012; Kim et al., 2009)
Underneath in box	Laserbased, PC, MOX	(Malaver et al., 2015; Pobkrut et al., 2016; Nunnermacker et al., 2008; Peng et al., 2015; Neumann et al., 2013)
Top	EC	(Roldán et al., 2015)
Side	EC and PC	(Villa et al., 2016b)
Different	PC	(Weber et al., 2017) (inlet top, sensor below), (Berman et al., 2012) (nosecone)

Research upto now has shown that detecting leakages for example with this type of sensor works very well. The sensor is affordable and reacts fast on high emission (Cross et al., 2017). Now it is slowly used for air measurements, this means that the sensor needs to react to lower emissions. This gives a couple disadvantages. The sensor has cross-sensitivity to other gasses, sometimes other gasses filter through the membrane and start the reaction. Another disadvantage is that the AE is not covering all the outside factors, the sensor reacts as well on humidity changes and temperature changes (Cross et al., 2017). This even differs between sensors, therefore each sensor needs to have extra calibration, besides the AE electrode, which will be further explained in section 2.4.

2.2.4 The available electro-chemical sensors

The electro-chemical sensor used in this research is as well used by Villa et al. (2016b); Neumann et al. (2013). These sensors are small and available from the company AlphaSense. This type of sensor is as well used in the researches of Jiang (2018); Villa et al. (2016b); Cross et al. (2017). The research of Jiang et al. (2016) had as topic to create a sensor system with the help of citizen science. This meant that with workshops citizens of Amsterdam developed sensors to place on locations which were important to them to monitor. The requirements for these sensors were that the sensor was sensitive enough the measure the typical present concentrations of NO_2 and it needed to be affordable. This resulted in the choice for the AlphaSense NO_2-B43F sensor (Jiang et al., 2016; Alphasense, 2017). To be able to use these sensors some hardware and software experience is needed, but this can be found in workshops and on the internet. This easiness in the development makes this sensors relatively easy to deploy. The company AlphaSense has two types of NO_2 sensors: B43F and the A43F. According to their website, the B-series is more focused on use at a specific location for a long period of time, while the A-series is more specific developed for portable use, so this sensor would be more useful to deploy on a UAV (Alphasense, 2017).

2.3 Sensor location on the UAV

After the sensor type is determined, the sensor needs to be placed on the UAV. This is a point of discussion within the development of sensor systems on UAV, within table 2.2 the options have been summarized as described by the articles used in this literature review. In the case of optical sensor systems, such as the optical particle counters or the spectrometer, the sensors are placed below the UAV. These sensors can easily be mounted underneath a UAV or airplane, because they are not as much influenced by the direct surroundings of the UAV.

The location for the placement of an electro-chemical sensor is still under discussion. The research of Roldán et al. (2015) states that the best location is on top of the UAV, while the research of Villa et al. (2016b) states that the best location of the sensor is on an arm of 1m outside the UAV. These articles state the contradictory. What mainly influences the choice of location with the electro-chemical sensor is the influence of the UAV rotors on the windflow around the UAV, and therefore on the amount of gas being able to reach the sensor. Roldán et al. (2015) estimated the wind effect by creating wind simulations of the rotors. Villa et al. (2016b) estimated the location by measuring with an anemometer around the UAV. Roldán et al. (2015) concluded that the windspeed above the UAV was higher than below the UAV, from which can be concluded that the sensor better can be on top of the UAV. Villa et al. (2016b) says the best is that the sensors are not influenced at all by wind, therefore they should be placed as far as possible from the UAV. Therefore they created an arm of 1m. Both have disadvantages. Roldán et al. (2015) sensor's are still influenced by the created wind and Villa et al. (2016b) sensors are too far from the UAV to have stable flight outside. Next to that, in practice the sensors are found underneath the UAV, such as the UAV as owned by RIKILT. No research upto now has quantified the influence mounting the sensors underneath the UAV has. Therefore more research on this topic can be done, quantifying the influence and making a proposed sensor location, which is as well giving proper results as well as being on an easy to use location on the UAV.

Then there is one last group, sensors placed in a box. These researches made a system which cause airflow through a tube or box. Next the sensor used measures within this tube or box the concentration. The advantage is that within such a tube or box the air is not influenced by rotors. The disadvantage is that it needs to be considered very well how the airflow is made through the tube or box. At this moment this system is not tested on electro-chemical sensors, but this might be a good option to reduce the influence by the wind from the UAV rotors.

2.4 Calibration of the sensor

2.4.1 Calibration methods

Many of the articles do not mention the calibration of the used sensors (Pobkrut et al., 2016; Berg et al., 2012; Kim et al., 2009; Neumann et al., 2013; Roldán et al., 2015) or mention that the used sensors are used as calibrated by the manufacturer (Villa et al., 2016b; Kurtenbach et al., 2016; Weber et al., 2017). Depending of the goal and the use of the research this can be done, for example when the research focuses on development of a system and therefore only to if a gas can be detected. As soon as the research starts to focus on determining the air quality, and therefore on the absolute amount of gas in the air, it becomes important that the sensors are calibrated.

Previous research has shown that trusting the calibration of the manufacturer is not enough and that more calibration needs to be done (Cross et al., 2017). The urge for this calibration differs per sensor type. Especially an electro-chemical sensor needs further calibration. The electro-chemical sensor is cross-sensitive to several gases as well sensitive to changes in temperature and humidity. Furthermore the electro-chemical sensor has the characteristic that the values drift off after a while of use. When a sensor is for a long period in the same place it most likely will under- or overestimate its values. Calibration in this case means finding new correction factors to correct this drift-off phenomena.

The static sensors this research is using are OurAir Kit, developed in the research of (Jiang et al., 2016). The kit contains the electro-chemical sensor of AlphaSense: B43F and a 16-bit analog to digital (A/D) converter (ADS1115) (Jiang et al., 2016). Mijling et al. (2018) did extensive research in which the best method for calibration within this use case was searched. Just the manufacturers calibration was found to be not precise enough (Mijling et al., 2018; Cross et al., 2017). Found is that electro-chemical sensors are cross-sensitive to ozone (O_3) as well as very sensitive to temperature changes and humidity changes. For example when the temperatures are close to 30 degrees Celcius, the amount of NO_2 drops down. The best temperatures to use the AlphaSense sensors are between 5°C and 25°C.

Calibration can be done in two different ways. First calibration can be done by comparing the results of the sensor with results of an official station. Within the research Mijling et al. (2018) the results have been calibrated by comparing the NO_2 results with an official station of the GGD (health centre) in Amsterdam. The sensors stood for 8 days next to this official station. After these 8 days, the data is gathered and with a multiple linear regression, a model was created which corrected the concentration for relative humidity and temperature. After the research period of a couple months the sensors went through such a calibration period again. This way the drift-off of the sensors was estimated, which could be taken into consideration for the months of measurement.

Table 2.3: Calibration methods used with type of sensor. CF stands for Correction Factor. EC for electrochemical sensor, PC for particle counter, MOX for metal-oxide sensor.

Calibration method	Sensor Type	Literature
Manufacturer	EC, PC	(Villa et al., 2016b; Kurtenbach et al., 2016; Weber et al., 2017)
Laboratory	spectrometer, EC	(Khan et al., 2012; Nunnermacker et al., 2008; Berman et al., 2012)
Model with CF	MOX, spectrometer, PC	(Malaver et al., 2015; Peng et al., 2015)
Not mentioned	EC, spectrometer, MOX	(Pobkrut et al., 2016; Berg et al., 2012; Kim et al., 2009; Neumann et al., 2013; Roldán et al., 2015)

Another calibration method which can be done is within a laboratory. This option is interesting for researchers which have the access to a laboratory. In this case the sensor does not have to be outside for a week and the sensors can be calibrated shortly before they need to be used. Cross et al. (2017) names the potential of using a controlled gas-box for faster, more precise calibration. This topic needs further research and is not extensively tested. In the literature found for this review, 3 articles write about calibration in a laboratory (Khan et al., 2012; Nunnermacker et al., 2008; Berman et al., 2012). Nunnermacker et al. (2008) used a spectrometer, which was calibrated in a laboratory. The others did not describe extensively how the calibration worked. Taking this together it means that the calibration of electro-chemical sensor on relative humidity, temperature and possibly cross-sensitive gasses need to be further explored and tested.

2.4.2 Influence from wind

The calibration done upto now for electro-chemical sensors are focused on temperature, relative humidity and cross-sensitivity to other gasses. What stands out that all different researchers name the influence of wind on the measurements. Several types of wind are mentioned: from the rotors of the UAV, environmental wind, the wind caused by the weather and the wind caused by the moving of the object to measure. The risks of these winds is mentioned as dispersion of the gas, which causes underestimation of the gas in the air. If this topic is researched and there is a linear correlation, with an higher wind, the amount of gas measured gets lower, while it is certain what the amount of gas input was, this can be taken into consideration as well in the calibration. This topic is upto now not researched, so needs several types of experiments, with outside and laboratory calibration, before this can be used.

2.5 Plume Detection

Passive and active sampling

Within the article Neumann et al. (2016) it is perfectly described why gas sensing with a UAV deserves some extra attention on plume detection. Within this article they speak of passive and active sensors, I called it in chapter 1 static and mobile sensing. Air quality research upto now makes use of static sensors, or what Neumann names passive sampling, to monitor over a large amount of time the general air quality, such as in Luchtmeetnet (2017). Not every minute the system is measuring, the sensors will detect an NO_2 plume, but still it gives data, because at some point the wind will blow the NO_2 plume over the sensors. This is different with the mobile measuring platforms, or as Neumann names the active sampling, the period of measuring is shorter. Depending on the system, the flight time for UAVs is around 10 to 20 minutes and for airplanes a couple hours. Even for airplanes it is in comparison with the static sensors a short amount of time for measuring emission. This causes that the plume of NO_2 needs to be actively searched to estimate the emission. And even with the UAVs, where to time is expressed in minutes, the plume measurements needs to be done effectively (Neumann et al., 2016).

The strategies used in the literature used are summarized in the appendices in the table A.1. Below the most interesting articles will be highlighted. It differs from educated guessing where the plume will be Berg et al. (2012) towards actively using the measurements real-time for determining the flight-plan

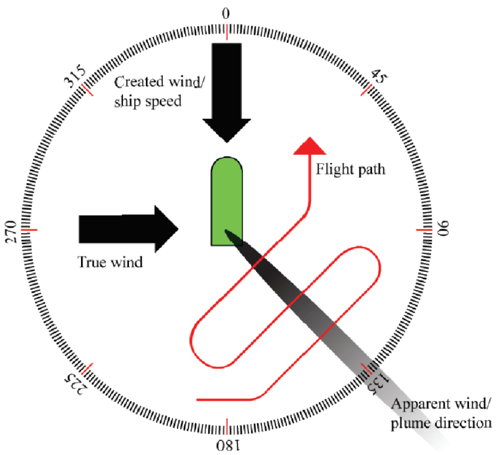


Figure 2.1: Flightpath of Berg et al. (2012), a perpendicular to the plume zigzag pattern, towards the ship. Plume direction calculated from wind direction + wind from ship speed forwards.

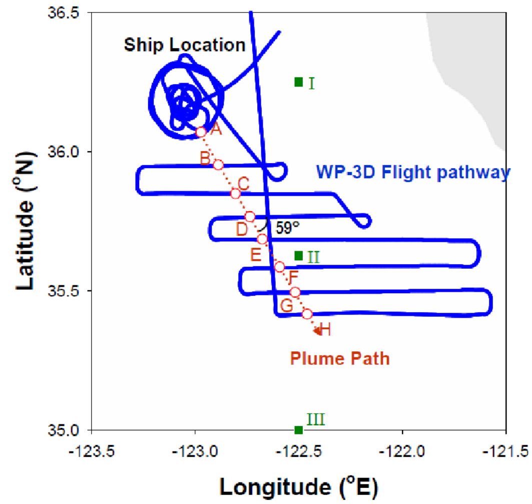


Figure 2.2: Flightpath of Kim et al. (2009), a zigzag pattern through the plume at 59degrees at 8 points + a circular pattern close to the ship.

strategy Neumann et al. (2013). What all of the articles have in common is that the wind determines a large path of the route planning. Only the seriousness of the wind effect is changing from article to article. To some level the wind is necessary to have a plume. As Villa et al. (2016b) was encountering that the NO_2 stayed around the emission source, so some draft in the hangar they were using was necessary to detect from a few meters the NO_2 concentration. While others such as in the articles where the emission plume of ships was detected with an airplane, calculated the wind direction and with that the flying direction (Berg et al., 2012; Kim et al., 2009). The difference found in measuring with an airplane versus flying with a UAV is that the UAV is much more effected by the wind as an airplane. The airplane covers a larger area, so more chance it was flying within the plume. Below this will be further explained, first in the articles with the airplanes, secondly for the UAV more specific.

Ships and airplanes

Large airplanes cover a large area, so have less the problem of flying within the plume. With UAVs as smaller instruments they have less flight time and also cover a smaller area as airplanes. This is for example visible in the article of Berg et al. (2012).Within this article SO_2 and NO_2 emission is measured with a spectrometer on an airplane. Because of the spectrometer the airplane needed to cross the plume perpendicular. The spectrometer measures sideways and by crossing the plume perpendicular, the largest part of the plume will get measured. The plume was assumed to be in the downwind direction, in figure 2.1 this is named as the true wind. Next to taking the downwind into account, the wind created by the ship moving forward is taken into account as well, this is named created wind. This created wind is calculated by taking the speed of the wind moving forward. Together this will form the apparent wind. Within the apparent wind direction the airplane made a zigzag flight path towards the ship. According to the authors this resulted in good results as regards the covering of the plume. The main uncertainties within this specific research had to do with errors caused by the scattering of the signal on the water surface.

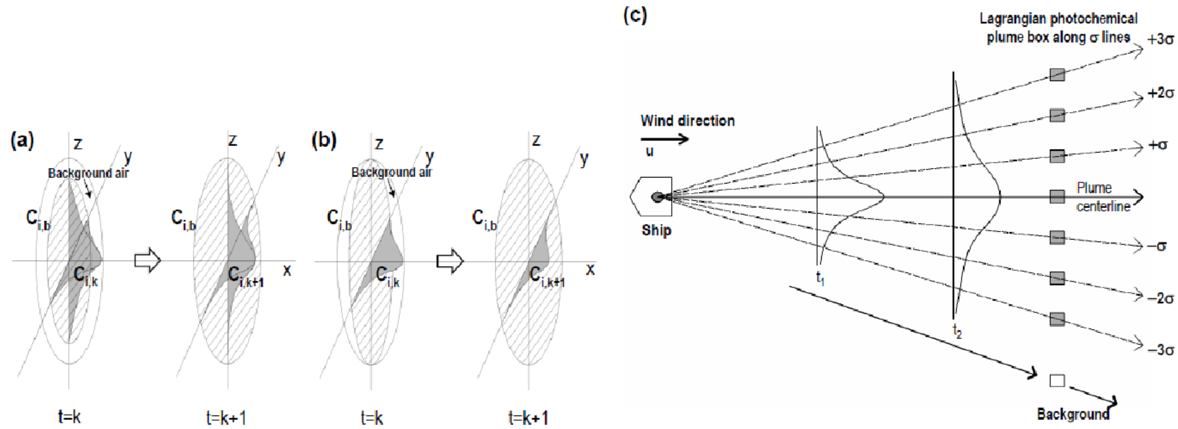


Figure 2.3: Within this image the plume distribution over time is shown as is researched in the research of Kim et al. (2009). It shows that the dispersion effect over time is quite large. t=k stands for time step, C_i, b stands for background concentration and C_i, k stands for plume concentration at given time step at center line.

The translation to UAV sensors

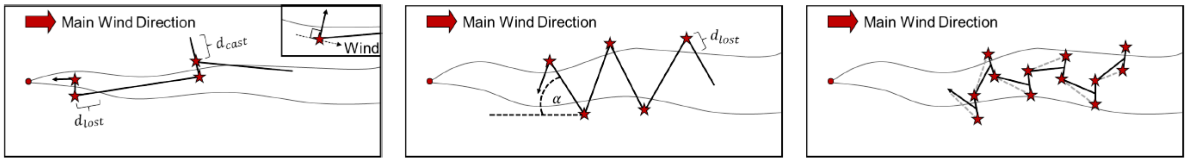
By having smaller systems and having less flight time with the UAV than with an airplane, respectively around 20 minutes against a couple hours, it needs to be preciser chosen where to measure. When choosing the location to measure it is interesting to see where to expect the plume. The interesting information is from a plume is the background concentration and the concentrations distributions within plume. The distribution of a ship emission plume is described by Kim et al. (2009) and is shown in 2.3. From the center line the plume disperses as an ellipse with at the x,y plane an Gaussian distribution.

What in general is done when measuring with a UAV an emission plume is first measure in upwind direction the background emission within the area. Secondly the emission is measured in the wind direction. Assumed is that the plume moves with the direction of the wind. By comparing the background with the higher values it is estimated where to plume is located or in some cases what the higher concentration is in the area (Khan et al., 2012; Malaver et al., 2015; Pobkrut et al., 2016; Peng et al., 2015; Weber et al., 2017; Berman et al., 2012; Neumann et al., 2013). The tactics for covering the complete width of the plume is approached different by each research. It changes from spiral (Peng et al., 2015; Kim et al., 2009), to measure at fixed points instead of continuously (Weber et al., 2017), to measure around a fixed route (Berman et al., 2012; Pobkrut et al., 2016).

Taking the wind direction as indicator for where the plume is located is more complicated as assumed. For example when there is a moving object, such as a ship, the speed forward needs to be taken into account (Berg et al., 2012). Next to that, with small changes of the wind direction, the plume is at a different locations, as Malaver et al. (2015) shows in their research.

To tackle the problem of knowing where the plume starts and ends Neumann et al. (2013) developed a new system of determining where the plume is located. Neumann et al. (2013) looked into the behaviour of insects when they use active exploration behaviour when they want to find the point of gas emission. This resulted into 3 algorithms which should be able to detect a gas plume. First these algorithms were tested on AGV (Automated Ground Vehicles) and within this research the step is made towards UAVs. Still the algorithms focus on the x,y plane and the height is not taken into consideration.

What the algorithms of Neumann et al. (2013) describe are the following. The first is the surge-cast algorithm. The second Dung Beetle or zigzag algorithm. The third Pseudo-Gradient algorithm, which are shown in figure 2.4. The first two algorithms use the plume information as binary information: measure gas above or below threshold. The surge-cast algorithm moves through the plume upwind, until



(a) Surge-Cast Algorithm (b) Zigzag Algorithm (c) Pseudo Gradient-based Algorithm

Figure 2.4: The developed algorithms by Neumann et al. (2013). Left is the surge-cast algorithm, middle the Dung Beetle algorithm, right the pseudo-gradient algorithm.

the value is below the threshold, then looks back for the plume by flying cross-wind, and then starts over again. The Dung Beetle/zigzag algorithm aims to cross the plume with a beforehand determined gradient, e.g. 60 degrees, as soon as the value is below the threshold, the UAV changes direction with 60 degrees upwind. The last developed algorithm, is not binary, but takes the measured concentration itself into consideration. First step 1 the sensors on the UAV calculate the wind and concentration and then makes an orthogonal step. The differential between the concentration and wind is calculated at this second point in comparison with the previous point, then a next step is calculated. At the third step, the sequence starts over again. The conclusion of the research was that a good correlation was found between the simulation and the outdoors experiments for the pseudo-gradient and the zigzag algorithm.

The algorithms above were programmed into the UAV flying system. This is only not always possible. Some UAVs do not have the possibility to program the flying path with such algorithms or make it hard to program. Besides that some programming knowledge is necessary before this can be used, which is not always in the scope of possibility. Still the results of Neumann et al. (2013) can be used. That the zigzag and the pseudo-gradient algorithms show good results can as well be found in the articles which are flying with an airplane (Berg et al., 2012; Kim et al., 2009; Nunnermacker et al., 2008). Therefore the flying techniques can still be used manually, to be sure to cover the whole plume.

2.6 Summary and Main Observations

2.6.1 Further research

From the above it becomes clear that more research can be done to the sensor development in the future. First the electro-chemical sensors can be improved in the future. At this point it has a high cross-sensitivity with O_3, which influences the measurements. This can be done by improving the quality of the sensors or by placing several sensors next to each other detecting cross-sensitive gasses. If all gasses are represented, or at least the cross-sensitivity gasses for the gas of interest, with the calibration the value can be corrected in a multiple linear regression model as is described in section 2.4. This is mentioned several times, only not used and executed in the previous researchers.

Not only placing more sensors on a UAV can be researched more, but as well the location of the sensors on the UAV. At this point the best location is contradictory in research. It is discussed on top or outside the UAV on a beam of 1 meter. Especially with quantification of the decrease of gas, because of the wind effect, will give new insights. A couple times research made use of a gas-tube to place the sensors in. This can be researched more as well for electro-chemical sensors specific, as it is now used mostly for Particle Counters sensors.

The calibration is written down a couple times, although mostly the manufacturers calibration is used. The researchers who did calibration, mainly used the outside-calibration methodology, but several times is mentioned that laboratory calibration can be of use in the future, but need for now more research before it can be used. Within the topic of calibration, calibration for wind might be an opportunity to research as well. If the effect of wind can be corrected with calibration it might help the easiness in use of the sensor.

Furthermore the influence of wind is mentioned several times. Partly the wind produced from the UAV rotors making the sensor location on the UAV important. Next the environment wind is mentioned as influence on the emission plume, which makes that strategies are necessary to find the emission.

Looking to the flight patterns to use for detecting a plume there are some interesting developments going on, such as the automatic plume detection of Neumann et al. (2013). This can be integrated more and developed upto it is more easy to use. As well as using the patterns as well in the altitude, which is an advantage of using a UAV, can be researched more. Next to the higher user friendliness of the flight patterns the algorithms need to be adjusted for using on different altitudes, at this moment this direction is not researched yet.

2.6.2 Chapter conclusion

Concluding with the research question for this chapter: What is known in literature about the development and use on electro-chemical sensor mounted to a UAV? It can be concluded that specific research on the electro-chemical UAV combination is not studied elaborately. Villa et al. (2016b) experimented with this specific system set-up and concluded that it would be best to have a system where the sensors are with a 1m beam outside the UAV center. When looking further outside this specific set-up more is known. For understanding which flight path could be useful, articles with other UAV sensor combination or airplanes were helpful to understand that zigzag and spiral are used flight paths. Next research on the electro-chemical sensor has shown that calibration of the sensor is important.

To conclude with the answer to the first sub-question, at this moment few is known about the use of an electro-chemical sensor mounted to a UAV. Villa et al. (2016b) experimented with this specific system set-up and did research in an indoor environment. When looking further outside this specific set-up, more is known making it possible to experiment with the specific UAV set-up outside. For understanding which flight path could be useful, articles with other UAV sensor combination or airplanes were helpful to understand that zigzag and spiral are used flight paths. Research specific on the electro-chemical sensor has shown that calibration of the sensor is important. Nevertheless more research on the specific NO_2 electro-chemical sensor mounted to a UAV is useful, as there is no conformity on which location the sensor should be mounted to the UAV. Next the outside use of this specific combination is at this moment not tested and experiment with.

Chapter 3

Evaluation Of The Sensor System: Methodology

Within this chapter what is learned from the literature study before, is taken into consideration and used to develop a methodology to be able to answer the main question: how to detect a plume with an electro-chemical sensor mounted to a UAV.

This chapter will exist out of 4 parts: first the materials & instrumentation will be shown and explained, secondly the experiment set-up will be explained, thirdly the calibration of the sensors will be explained and fourth the data analysis methods are described. During the third part, the calibration, the results and analysis of the calibration data will be described as well. These results impacted the analysis method and therefore are easier to understand when explained in this chapter.

3.1 Materials & Instrumentation

The core of this research is the electro-chemical sensor. As in the literature chapter is described the electro-chemical sensor is small, which makes it easy to mount underneath the UAV. In researches using an electro-chemical NO_2 sensor, multiple times the AlphaSense sensor is used Jiang et al. (2016); Villa et al. (2016b); Cross et al. (2017). Therefore for this research the brand of AlphaSense sensors is chosen to use. For measuring NO_2 two types of sensors are available of AlphaSense: the NO_2-A43F and the NO_2-B43F. The NO_2-A43F is smaller, 20mm, and is especially designed for mobile air quality network. The NO_2-B43F is larger, 35mm, and designed for fixed and static air quality networks, therefore this sensor is more reliable on the longer term. Further these two type of sensor work the same as the working of it is explained in chapter 2.2.3.

Within this research both type of sensor are used. First the NO_2-A43F is mounted underneath the UAV to measure the NO_2 emission with the UAV. Secondly the NO_2-B43F is used in 3 static sensors. An earlier version of the static sensors used in this research, is used in the research of (Jiang et al., 2016).

3.1.1 UAV Set-Up

This research was able to make use of the UAV set-up as was developed by ROBOR Electronics B.V. in cooperation with RIKILT Wagenignen University & Research. ROBOR Electronics B.V. is a company specialized in developing wireless sensors and RIKILT is the research institute specialized in doing research around the topic of safe food and feed.

The UAV is the DJI Matrice 100, which is specifically useful for research, because new sensors can

(a) Top view UAV (b) Sensors mounting point UAV

Figure 3.1: Figure 3.1a shows the above view of the UAV used during this research. It is the UAV DJI Matric 100, owned by RIKILT Wageningen University and Research. Figure 3.1b shows how the sensors are mounted underneath the UAV. The sensors are the AlphaSense sensors for NO_2,CL_2, H_2S and SO_2, all of the A42F series, the series which are specially designed to be smaller and useful for mobile platforms.

be attached to it relatively easily. For measuring gas four AlphaSense sensor are placed on the UAV: NO_2, CL_2, H_2S and SO_2. All this sensor are of the AlphaSense A43F series, which is a series specifically designed to be used on mobile platforms such as the UAV. Furthermore 4 smaller sensors are mounted to the UAV, TGS2600, TGS2602, TGS2610 and TGS2620. These sensors are more general detecting air contaminants and other Volatile Organic Compounds (VOCs). In figure 3.1 is visible how the UAV set-up looks like. Within this research only the AlphaSense NO_2 is used as that is what this research is interested in measuring the air pollution by the gas NO_2. The UAV had 8 batteries each being able to fly for around 20 minutes, giving the possibility to fly 160 minutes on one experiment day. The sensors of the UAV were wireless connected with the computer, which made it possible to get data in semi real-time by refreshing the data imported through excel.

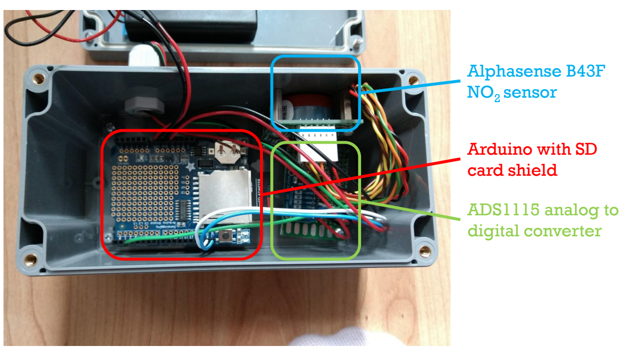
3.1.2 Static Sensors Set-Up

Within this research 3 static sensors are used. Static sensors are used more elaborate in earlier research as the sensors on the UAV, which makes it useful to measure with and better know what values to expect. As example for this research the sensors of (Jiang et al., 2016) are used and developed further. This static sensor system is named OurAir Kit. The most important part of the OurAir Kit are the AlphaSense sensors: NO_2-B43F. Furthermore this sensors contains a 16-bit analog to digital (A/D) converter (ADS1115) and a temperature and relative humidity sensor, which is useful later in the calibration. It is all connected by an Arduino Uno, with a SD-card shield for storing the data. The sensor works on a battery attachment with four AA-batteries, but these batteries can be replaced by a power plug, when the sensors needs to measure for several days.

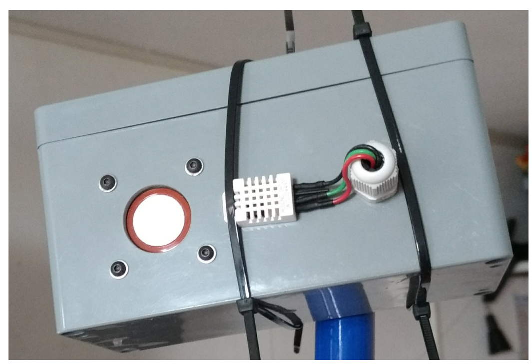
3.1.3 Supplementary Materials

The UAV with sensors and the three static sensors are the most important materials used in this research, but more materials were needed to execute the experiments. First the emission source for conducting the

(a) Side view three used OurAir Kits



(b) Inside OurAir Kit components



(c) Front view static sensor: OurAir Kit

Figure 3.2: Figure 3.2a show the three static OurAir Kit sensors available for this research. The sensors are built in a waterproof housing. Figure 3.2b shows what is inside an OurAir Kit. The OurAir Kit contains the AlphaSense NO_2-B43F sensor, 16-bit analog to digital converter (ADS1115), a temperature and relative humidity sensor, Arduino UNO, SD-card shield and energy supply from batteries. In figure 3.2c the frontview of the OurAir Kit is visible, showing the NO_2 sensor and the temperature and relative humidity sensor.

experiments with: this was the tractor Deutz Fahr DX4.11. SE.

- Emission source: tractor, Deutz Fahr DX4.11. SE with a diesel engine of 3.3L
- Anemometer: hand held anemometer to measure the wind speed on the location
- Measuring tape to estimate distances

3.2 Experiment Set-Up

Within this section the methodology for doing the experiments will be described. This is split into three parts according to the three questions in the second sub-question.

The goal of the experiments is to gain insight in mapping NO_2 emission. With these experiments the goal is to see if differences can be seen with different flight paths, flying on different heights and flying on different days. Insights gained with these experiments can help to make experiment design choices and use of the system in the future.

The UAV was experimented with on 3 separate days. The first day, referred to as day 0, was more an experimental day in which several flying patterns, among which random flying, was tried to detect what kind of values were there to expect. On this day it became clear that the wind must be taken into consideration during the day and that chosen a flight-path covering a large area is important to see the spread of the NO_2. Taken the literature into consideration this resulted in two experiments: spiral flight path and zigzag flight path. On the remaining 2 experiments days, referred to as day 1 and day 2, these two flight paths have been repeated several times to have large comparable data set. The pre-measurement day will not be considered any further.

During all the experiments three static sensors are used. The sensors used are developed further from the sensors developed in (Jiang et al., 2016) and called OurAir Kit. These sensors are used for a longer period, and measured for several months the NO_2 in Amsterdam. During the experiments the static sensors are placed at 5meters from the emission source at 3 different heights, 3m, 4m and 7m. At this location the sensors will measure during the whole measurement period. Expected is that the wind will have a large influence on the NO_2 plume, spreading the plume over the area. Therefore it is expected that the static sensors will be shortly exactly in the plume, and then again out of the plume. When this happens it supports the research question on measuring with the UAV in wind. Next for this research question, the static sensors are placed at the same three different heights as the UAV will measure. Therefore it is expected that the UAV and the static sensors will show the same differences in the different heights. In this case the static sensors function as validation methods for the differences in height.

3.2.1 Different Flight Methods

In order to compare flight methods, within this experiment two flight methods will be experimented with. The set-up of these experiments are explained below.

Zigzag flight path

The zigzag flight path is based on the research of Neumann et al. (2013); Kim et al. (2009); Berg et al. (2012). The idea is to fly 15meters in the wind direction and during the flight make 60° turns. This way a large area is covered in the wind direction. The zigzag pattern is executed on 3 different heights: 3m, 4m and 7m. During one experiment day, 3 batteries are fully flown with this flight pattern. Within each battery the pattern is executed 4 times at: 3m, 4m, 7m and 4m again. The experiment set-up is graphically shown in 3.3.

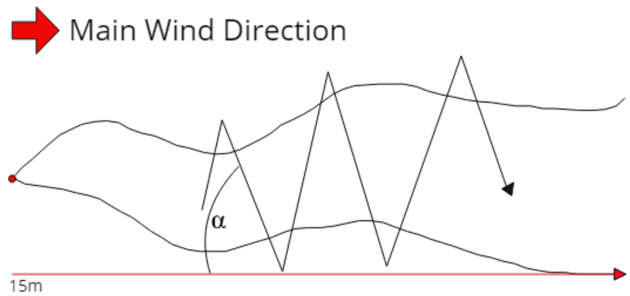


Figure 3.3: Within this figure the experiment set-up is shown of the zigzag experiment. The red dot is the emission source. Through the plume in the wind direction the UAV flies a zigzag pattern. α, the corner for the zigzag, is 60°. The zigzags are executed on a distance of 15m from the source.

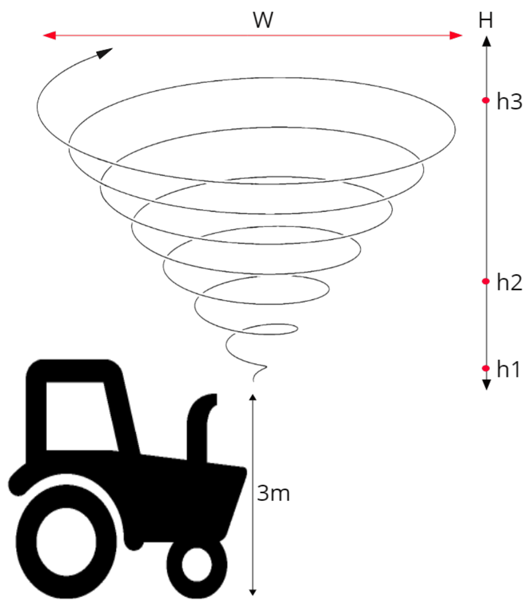


Figure 3.4: Within this figure the experimental setup is shown of the spiral experiment. The outlet of the tractor is at 3m heights. Through a spiral which is getting wider to the top and ends in W=15m. The height is 7m. At the right the heights with the red dots are shown for the static sensors. These are at 3m (h1), 4m (h2) and 7m (h3).

Spiral flight path

The spiral flight path is mainly based on the research of Peng et al. (2015). During this flight pattern the pattern starts with a small circle at 3m height close to the emission source. Slowly the circles get wider and higher until it reaches the height of 7 meters and a width of 10 meters. This flight pattern gives an overview of the spread of NO_2 over the area as well as the spread of NO_2 in height. The experiment set-up is graphically shown in 3.4.

3.2.2 Different Wind Speeds On Different Measurement Days

The data is gathered on two separate days, 15^{th} of June and 20^{th} of June. The weather on both these was different, to research the influence of weather circumstances on the weather. Both days the experiments have been executed in the morning and partly afternoon. The first flight on June 15^{th} started at 9:54

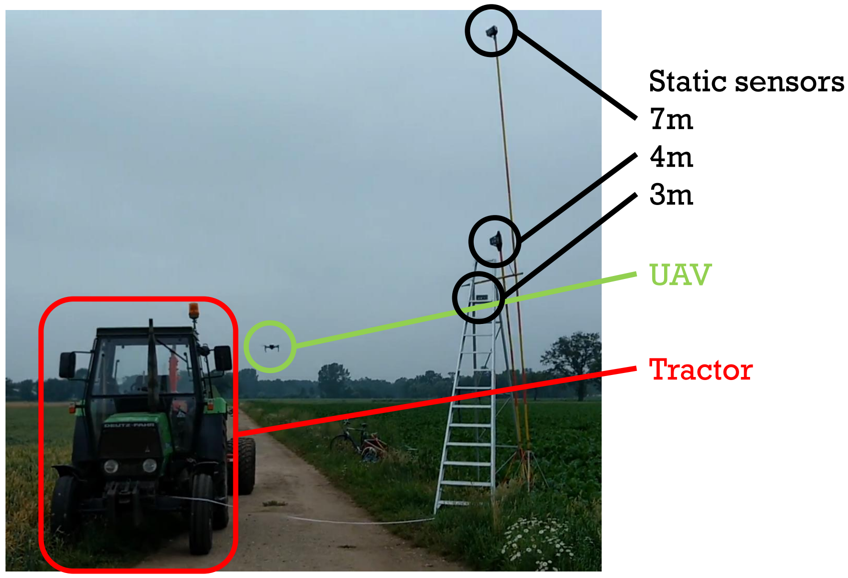


Figure 3.5: Within this figure the experiment set-up is shown of the experiment as was executed on the 15th and 20th of June 2018. In the red box the NO_2 emission source is visible. In the green box the UAV used during this research is shown. The UAV flew through the open space as is seen in the figure. In the three black boxes the static sensors, the OurAir Kits are shown. These were measuring during the whole of the experiment at 3m, 4m and 7m.

and the last flight ended at 14:01. The first flight on June 20^{th} started at 9:35 and the last flight ended at 13:06. The weather on the 15^{th} June was warm and sunny with low wind. It was 24°C and the wind we measured was a minimum of 0.0 m/s and a maximum of 2.9 m/s. The humidity as measured by KNMI was around 70%. On the June 20^{th} it had a bit more clouds in the morning and therefore a bit cooler. The temperature was around 20°C and the wind we measured had a minimum of 2.1 m/s and maximum of 5.3 m/s. The humidity as measured by KNMI was around 79%. With these experiment moments the outcome is very likely to have a nice comparison between the two days of experiment. Both have temperature under 25°C, which is a requirements for the sensor. The first day had low wind speeds and the second day had higher wind speeds, so this can be a good comparison. The wind direction on both days was similar in North East direction. The characteristics of the measurement days are summarized in table 3.1.

3.2.3 Different Heights

The zigzags have been executed on 3 different heights: 3 meters, 4 meters and 7 meters. As a battery-life is long enough to fly 4 zigzags each time the three different heights are flown, afterwards the 4 meters

Table 3.1: Table summarizing the weather circumstances on the 15^{th} and 20^{th} of June during the experiments.

Day	Start	End	Temperature	Humidity	Wind speed	Wind direction
June 15	9:54	14:01	24°C	70%	0.0 m/s-2.9 m/s	NE
June 20	9:35	13:06	20°C	79%	2.1 m/s-5.3 m/s	NE

zigzag is repeated again. On both days there is flown the spiral method as well. This spirals started at 3m and ended at 7m. To still be able to say something about the differences in height measured, each flown spiral, three spirals during each battery-life, is split in three equal parts indicated as: low, mid, high. Afterwards the heights can be compared and it can be said what the height of an effect has on the measurements.

3.3 Calibration Of The Sensors

As said in chapter 2 section 2.4 it is wise to calibrate the sensors extra besides the manufacturers calibration in order to measure meaningful results. Over time the sensors have the tendency to drift off the manufacturers calibration. The articles found mention calibration shortly. Mainly two types of calibration are used: laboratory calibration and outside calibration. In laboratory calibrations the sensors are placed in a closed box and it is exactly known how much of the gas of interest is emitted. The outside calibration uses other already calibrated sensors. By comparing the to-be-calibrated sensors with the calibrated sensors, the sensors get calibrated. With both of these methods this research did experiments to see its possible use.

Both types of calibration have the same way of correcting the sensor for the effect in output by cross-sensitiveness of gasses and relative humidity. The AlphaSense sensors work with the principle of a Working Electrode (WE) and an Auxiliary Electrode (AE). This Auxiliary Electrode is the manufacturer calibration. This sensor measures the changes in temperature and humidity and forms the correction counts for the WE. This means that WE minus AE forms the real counts output. These real counts can be converted to $\mu g/m^3$, as a realistic output of NO_2. The conversion is based on Mijling et al. (2018). With the calibration a multiple linear regression is executed. This shows the factor a parameter adds to the output. The parameters taken into account are WE, AE, temperature (T) and relative humidity (RH). The formula which shows this principle is Model D in the article of Mijling et al. (2018):

$$NO_2 = c_0 + c_1 * S_{WE} + c_2 * S_{AE} + c_3 * T + c_4 * RH \tag{3.1}$$

Within this formula the c_0 is an offset factor and c_1 to c_4 are correction factors showing the portion the WE, AE, T and H adds to the NO_2 value. This model can be more improved by adding as well a factor for O_3, but within this research the sensors measuring O_3 were not available.

3.3.1 Laboratory Calibration

The laboratory calibration is only experiment with changes in temperature and relative humidity. It was meant to also test with letting in pure NO_2 gas, but the delivery of the gas takes longer as the time for this research. Still the calibration gave some interesting insights.

Within the laboratory only the absolute 0 experiment is executed. This means that all the gasses are driven out of the gasbox, this way the sensor cannot react on possible NO_2 in the box, as well as it cannot react on other gasses it is cross-sensitive to, such as O_3. When this happens the sensor should give the result of 0 $\mu g/m^3$. The gas used to drive out all the gas is nitrogen (N). The end-result is not only determined by the amount of gas, but as well by the relative humidity and the temperature. Therefore these variables need to be varied as well. This can be done by bubbling method the gas first through water. With this bubbling the relative humidity is around 60%. When the bubbling through the gas does not happen, the relative humidity is 0%.

The first set-up is shown in figure 3.6. Within this set-up the nitrogen is directly let into the box, which can be seen left below. The output is right above. There are two options, actively pump out the gas with a pump, or having a natural flow by let the output opened. Chosen is for the last one. This way the flow in was equal to the outflow, which gave a stable situation in the gasbox. The three static sensors are placed on the floor of the box, while the UAV sensors are hanging on the place especially designed for this purpose. The measurements took place for 3 hours. The experiment was conducted for this long period, because a stable situation was reached only after 55 minutes, because it takes some time until the humidity in the box is from the humidity level in the laboratory to 0%. As can be seen later with the situation with a higher humidity, the stable situation is reached sooner. With the decrease of the relative humidity the temperature rose to a maximum of 30°C.

The second set-up is shown in figure 3.7. Within this set-up the nitrogen is first let in a box with water and from this waterbox it is let into the gasbox. This resulted in a humidity of 60% in the box and a temperature also in this experiment around 30°C. The humidity in this set-up is realistic to an outside situation. Although the humidity is higher, still there is a complete absence of NO_2, so the output should be $0\mu g/m^3$.

Laboratory Calibration Results and Analysis

The temperature during both experiments, with and without water, are similar: 30°C, see the middle graphs in figure 3.8a and 3.8b. The relative humidity is the main difference between both. During the dry experiment the humidity drops down to very close to 0%, as is visible in the lowest graph in figure 3.8a. At the point at 8000 measurements the humidity rises very quickly. This is due to stopping the inflow of nitrogen and starting the pump to clean the gas-box. During the water experiment the relative humidity is relatively stable around 60%, as can be seen in the lowest graph in figure 3.8b.

The influence of the temperature and the humidity is visible in the highest graphs in figure 3.8a and 3.8b. This shows the counts, the RAW output as measured by the UAV sensors, which is shown as working electrode (WE) minus auxiliary electrode (AE). In the dry test the process of going to a humidity of 0% can be recognized in the counts, as it shows a simultaneously a similar trend. This is the same in the last part of the dry test, when the inflow of nitrogen is stopped and the humidity increases again, the counts react immediately, by increasing as well. The water experiment shows relatively stable trend, corresponding with a more or less stable trend in humidity.

Overall the laboratory calibration shows that variation in relative humidity is possible. When in future research as well the pure NO_2 gas can be used for calibration this can give some extra insights. Then this calibration can be a relatively easy calibration method for the sensors.

3.3.2 Outside Calibration

The outside calibration is completely based on the research of Mijling et al. (2018). The basic principle is that the sensors are placed outside next to an official and calibrated measurement station. Then it is known what the output has to be of NO_2. The calibration period is several days. This makes sure that there are different amounts of NO_2, different temperatures, for example caused by the differences day and night and different relative humidity values. After this calibration period, multiple linear regression is executed which will give the C_0 to C_4 of formula 3.1.

Outside Calibration Methodology and Experimental Set-Up

Within this research the calibration period was from the 7th of June 2018 11:00 AM until the 13th of June 2018 15:15 PM. The sensors were placed next to the official measurement and calibration station of the RIVM, Rijksinstituut voor Volksgezondheid en Milieu, which is the Dutch institute for public health and environment. This station is situated on the terrain of the main RIVM building in Bilthoven. The sensors brought here, were the 3 static sensors of OurAir Kit and the sensors of the UAV. The sensors of the UAV can be detached from the UAV, as was as well visible in the laboratory gas-box. With the cover of the gas-box a system was created that the sensors had a small roof but was open to the side, this is visible in figure 3.9. This way the sensors were protected from sun, rain and wind, but the NO_2,

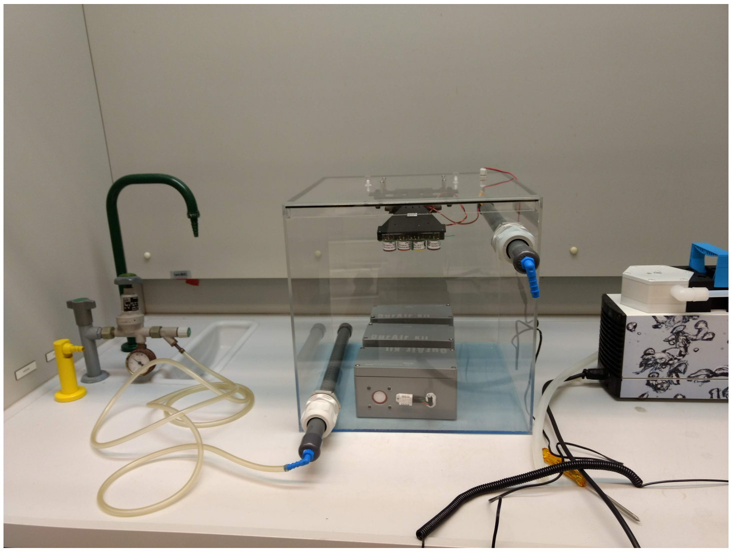


Figure 3.6: Laboratory calibration set up. Left the N_2 gas is let into the gasbox. In the gasbox the static sensors is placed on the bottom in the middle of the box. The UAV sensors are mounted on the top. Right above is the gas outlet. This outlet can be attached to the pump on the most right. The pump is only attached in the end of the experiment to clean the box.

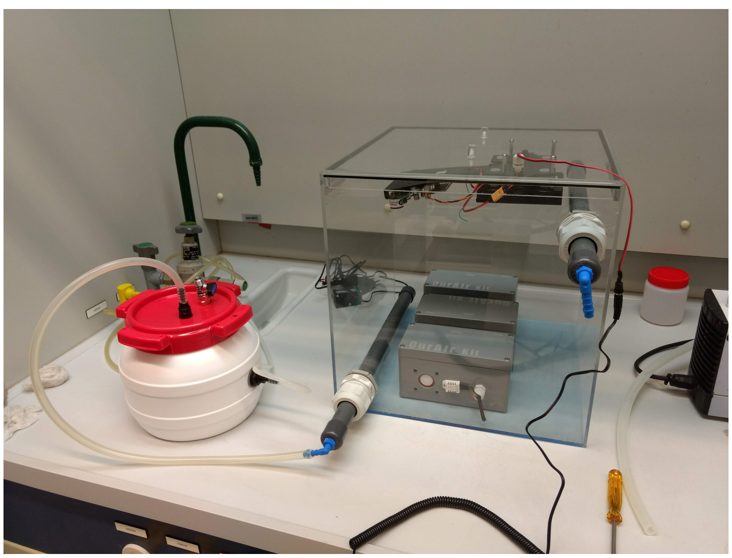
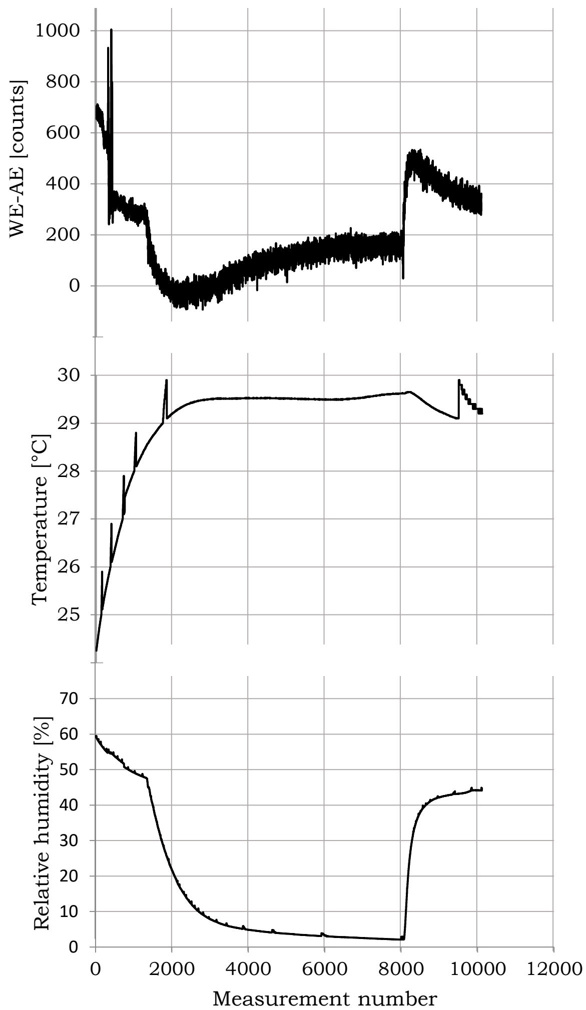
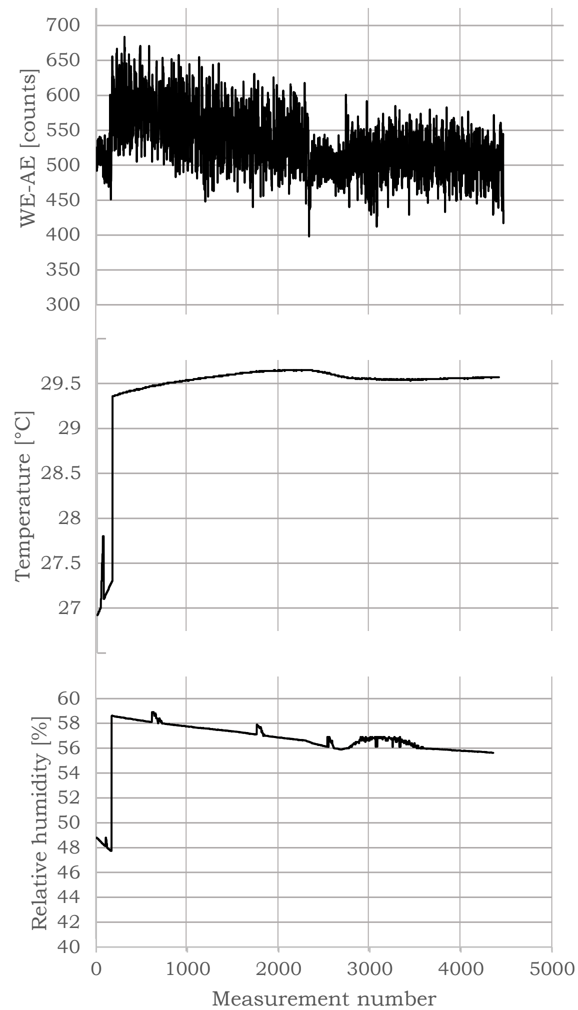


Figure 3.7: Laboratory calibration set up. Left the N_2 gas is let into the gasbox. In this set up the N_2 inlet is attached to the waterbox. Next the waterbox is attached to the gasbox. This makes sure that the relative humidity is around 60% in the gasbox. In the gasbox the static sensors is placed on the bottom in the middle of the box. The UAV sensors are mounted on the top. Right above is the gas outlet. This outlet can be attached to the pump on the most right. The pump is only attached in the end of the experiment to clean the box.



(a) Dry test



(b) Water test

Figure 3.8: This figure shows the course of the counts, the temperature and the relative humidity during the dry and water laboratory experiments. The figure 3.8a shows the dry test in which the N_2 flows directly into the gas-box. The figure 3.8b shows the water test in which the N_2 flows first through the water-box, before it enters the gas-box. This influences mainly the humidity which is now more close to 60%. The temperature in both experiments is around 30°C.

Figure 3.9: Set up of the UAV sensor for outside calibration. The sensors are attached to the plastic at the bottom. On top of it an aluminum screen is placed which protects the sensor from rain. The rock is placed on top to keep the aluminum screen on its place. Still enough space was opened at all sides to get enough airflow through.

Figure 3.10: Set up of the calibration system of the static sensors. The three static sensors are placed next to each other, all with the sensor side turned inwards. On top of it a plastic screen is placed with a brick on top to keep the plastic screen on its place.

Figure 3.11: The complete set-up of the outside calibration system with the UAV sensors at the complete right, static sensors at the complete left and the RIVM official sensors in the white mushrooms on the background.

temperature and humidity were still able to reach the sensors. The static sensors were placed next to each other with a plastic protector on top, this way the rain was not able to flow to the sensors, this is visible in figure 3.10. All sensors tops were secured with a brick, this way the wind was not able to blow away the roofs. In figure 3.11 the whole set-up of the system is shown. The white mushrooms seen in the figure are the sensor stations of the RIVM. The data output of the UAV and static sensors are per second. The data delivered by the RIVM is minute-based and delivered as well as hourly data. The data will be calibrated on the minute-based data.

With the software R the secondly based data is aggregated to minute based data and put in the model of Multiple Linear Regression. During this week the weather was two-folded: one one hand extremely sunny with high temperatures onto 30°C. And on the other hand had very heavy rain showers, which caused humidity of 100%. The trustworthiness of the sensors are decreasing with mainly this high temperatures. The best results are obtained with a maximum of 25°C. The last one and a half day (Tuesday 12^{th} of June and Wednesday $13th^{th}$ of June) the weather data was more ideal for calibration with temperatures around 20°C.

Outside Calibration Results and Analysis

After the data gathering the data is aggregated from second data to minute data and this is compared to the minute based NO_2 values of RIVM. The extreme weather conditions were visible in the data. To have a higher chance of succeeding, the last 3000 minutes are taken into account, which covers the last one and a half day which had lower temperatures and humidity. These 3000minutes are roughly 1/3 of the complete calibration period, which lasted 9000 minutes. On this part of the data the exploration of the data and the multiple linear regression is done. What appeared to be is that the RIVM official station is at their main building, which is in the green area of Bilthoven. Close to this area are no highways, ships, industry or other NO_2 pollutants. Therefore the NO_2 is during the whole period around $0\mu g/m^3$. When this data is shown in a scatterplot together with the parameters WE, AE, T and H, it is shown that no correlation can be found. See third column of table 3.2, within this table the results of the parameters as measured by the UAV sensors are shown. The static sensors showed very similar patterns as shown in this table. This scatterplot gives already an indication that there is very low concentration between the output, the NO_2, and the input, the parameters. A high correlation would have been better for the multiple linear regression. Next to this check on correlation, another check is executed: creating histograms. With multiple linear regression it is assumed that the data is linear. When a histogram is normally distributed it indicates that the data is linear. When this is not the case the data can be manipulated in order to get linear distributed. In this research several transformations have been tried, such as square root, cube root and logarithmic. Logarithmic transformation is shown in table 3.2 in the second column.

Executing the multiple linear regression for as well the normal data as the logarithmic transformed data gave the results as is visible in the tables 3.3 and 3.4. The R^2 is the highest for the UAV sensors with 0.1115 for the normal data and 0.1177 for the log data. This confirms the low correlation between the parameters and the NO_2 values of the RIVM as were expected with the results of the histograms and the scatterplots.

Outside Calibration Summary and Main Observations

Taking the results together from the outside calibration it can be concluded that the data at this point is not useful for calibration for this specific research, due to several factors.

1. Measurement location with low to no NO_2 emission
2. Measuring during a warm period, with temperatures over 30°C
3. Measuring during a period with high humidity

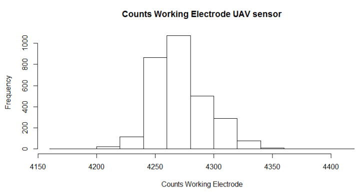
The first reason the calibration did not succeed is because there was low to no NO_2 emission. Actually the same problem as in the laboratory experiment occurred, only the 0 point can be calibrated. To have a proper calibration several NO_2 points are needed to create a linear correlation through those points to estimate the following points. At this point there is only one NO_2 point: 0. Therefore in the future NO_2 measurements needs to be done closer to emission sources, such as close to a high way. The RIVM has stations there as well, although these are not the official station, the stations have calibrated sensors, so the data cam still be calibrated.

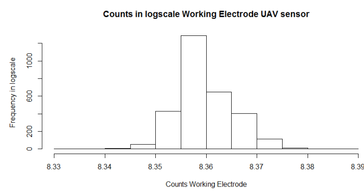
The second and third point is that the calibration period was too warm and humid, which caused that a large part of the data could not be used (2/3th of the data), because it was exceeding the boundary of when the sensors are measuring trustworthy results. Several improvements can be made to have better results. First do the calibration in a period when the weather is not warm and humid. What has to be taken into account in this case is that the calibration is still close to the moments the sensors are going to be used, because the longer between measurements and the calibration, the more the UAV sensor drifts off and need to be calibrated again. Another option might be to be flexible in time for how long the calibration lasts and take the sensors as soon as there has been a couple days of weather matching the requirements. As this method of calibration is already proven by Mijling et al. (2018), this calibration period needs to be taken more time for in the future to succeed.

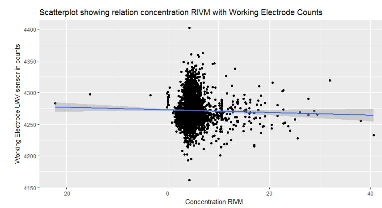
In the future this calibration can be really useful and successful when a measurement period is chosen without extreme weather and when the sensors are placed at a station which is for example located next to a highway. This way the temperatures are higher than 5 degrees and lower than 30 degrees. There are no extreme rain showers, causing high relative humidity. And when located next to a highway there will be NO_2 emission to measure.

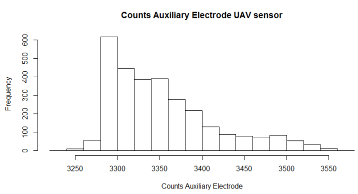
Table 3.2: Exploration of the results of the outside calibration period for 3000 records in which had an appropriate temperature of under 30°C as was measured by the UAV NO_2 sensor. In the left row the histogram of the values is visible, the middle row the log values histograms and the right shows a scatterplot in which the measured values are compared with the RIVM values. As a normal distribution is hard to find in both histogram types and no relation is found between the RIVM values and the measured values, it already indicates that the multiple linear regression analysis will not be succesfull.

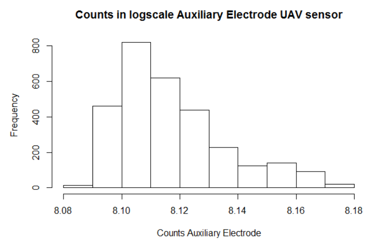
Histogram Normal values	Histogram Log Values	Scatterplot

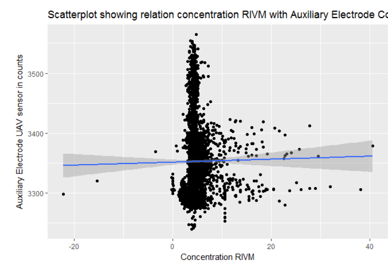


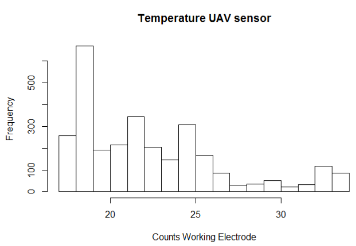


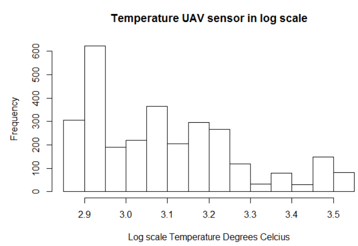


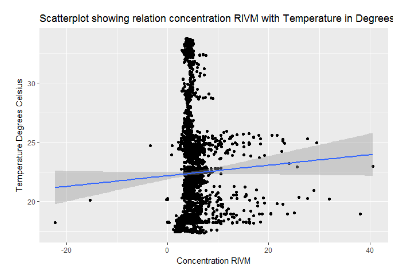


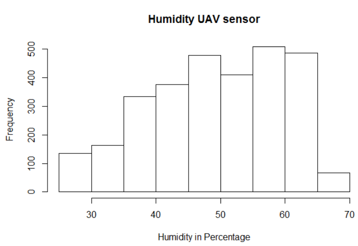


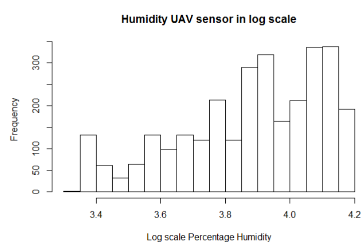


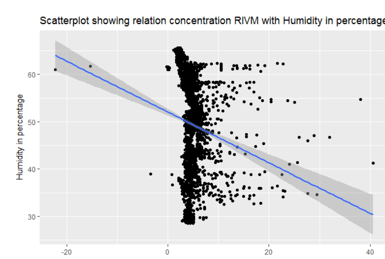


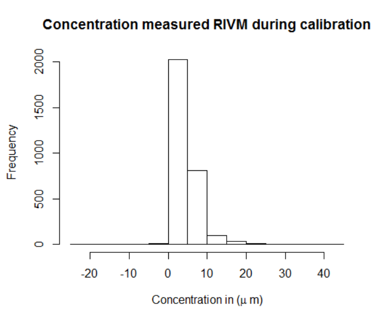












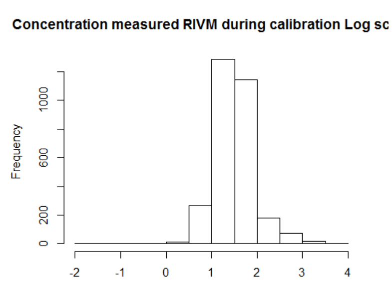


Table 3.3: The multiple linear regression executed on the data as measured by the UAV sensor without transformations

Sensor	C_0	C_1 (WE)	C_2 (AE)	C_3 (T)	C_4 (RH)	R^2
UAV	2.334029	0.011751	-0.007451	-0.444814	-0.254585	0.1115
Static 1	12.932861	0.001527	0.005758	-0.388086	-0.116806	0.0624
Static 2	-9.006954	0.007710	0.009191	-0.143400	-0.057722	0.03993
Static 3	14.8537228	0.0005553	0.0001647	-0.2705259	-0.0773560	0.07282

Table 3.4: The multiple linear regression executed on the data as measured by the UAV sensor with logarithmic transformations

Sensor	C_0	C_1 (WE)	C_2 (AE)	C_3 (T)	C_4 (RH)	R^2
UAV	-10.7698	13.2649	-11.0705	-0.6746	-1.7170	0.1177
Static 1	-33.0197	-0.5469	5.2750	0.4377	-0.0561	0.04769
Static 2	-56.14121	3.46602	4.40000	0.62522	-0.06963	0.06448
Static 3	-47.21331	1.44904	5.85630	-0.26108	-0.61111	0.07474

3.4 Data Analysis Methods

3.4.1 Data Analysis Method: Metric For Comparing Results Without Calibration

As can be read from the previous two calibration methods, calibration is very useful to be able to compare the several sensors with each other and to compare the values of several measurement days. Only the calibration needs to be done close to the actual measurement days, because of drift in the sensor. The calibration results did not turn out to be as successful as was expected. First of all in the laboratory calibration the NO_2 gas is needed, which delivery takes longer than this research lasts. For the outside calibration the weather circumstances were not ideal with some extra unexpected warm days and with a a not ideal station location. In this case this research proposes a metric which still makes it possible to compare the different sensors with each other and to compare the different measurement days.

Best is to have a metric which shows a relative value from a threshold which is unique for each sensor or experiment day. What is unique for each sensor and each experiment time is the background measurement. On each experiment day first a background measurement is conducted. This background experiment existed out of 2 phases of each 5 minutes. The first 5 minutes the UAV was on the ground so the rotors were off. This way the background value without possible distortion of the rotors is measured. Secondly the UAV flew for 5 minutes and measured the background concentrations in the air.

This background measurement should not detect any NO_2. Only what appears to happen with the sensors is that it shows a lot of fluctuation during its measurement, so it is hard to take one background value. The values fluctuate very quickly, even in a period just seconds apart from each other. This cannot only be explained by changes in temperature and humidity, but looks like noise. Therefore the value taken as background concentration needs to be chosen carefully. Next to that the noise makes it harder to detect what is a peak of NO_2 emission and what is a peak caused by noise. While the peak of NO_2 detection is the interesting thing to know. Taking the average from the background concentration and calculate the peaks from this value, might give more peaks than with certainty can be said. To be able to say that a peak is a real peak with a high certainty the following can be calculated, the background value is calculated with the help of the average of the background measurement, the standard deviation is calculated for the spread of the values and thirdly a confidence level of 95% is chosen.

The confidence level can be determined with the inverse normal cumulative distribution function,

Table 3.5: Calculating the metric of percentage of the measurements above the background value, further referred to as measurements of M.A.B., in comparison with the total amount of measurements for the dataset of the outside calibration at the official RIVM station as is measured by the UAV sensor. The expected result is that there is 0% of M.A.B. measured during this period, which is indeed visible from the calculation.

What	Calculation method	Outcome outside calibration UAV dataset in counts
Mean	calculate mean of background measurement	203.51
Standard deviation	calculate standard deviation of background measurement	136.36
Confidence level	95% confidence level	0.95
Threshold	$\texttt{invnorm}(\mu = 203.51; \sigma = 68.71; P = 0.95)$	316.69
Measurements > confidence	count the measurements which exceed the threshold	293
Total measurements	count the total measurements done	915
Percentage of M.A.B.	$\texttt{percentage M.A.B.} = \frac{293}{915} \cdot 100$	32%

further in this research named invnorm. Calculating the threshold with invnorm needs as input the mean of the background concentration measurement, further mentioned as μ, the standard deviation of the background concentration measurement, further mentioned as σ, and as third a beforehand determined confidence interval of 95%, further mentioned as P=0.95. Together this can be described as the formula shown in equation 3.2.

$$\texttt{invnorm}(\mu; \sigma; P = 0.95) \tag{3.2}$$

Next when is known what 95% that a measured value is above the calculated threshold, we known what are the measurements above the background value. The goal of the research is evaluating if a plume can be detected by an electro-chemical sensor mounted to a UAV. It can be determined if the plume is detected with this threshold. To be able to compare measurement days and to compare the static sensors with the UAV sensor the amount of measurements showing a peak can be counted. To make it comparable these counted the measurements above the background value can be calculated as a percentage of the total amount of measurements during an experiment. This percentage shows the percentage M.A.B. of the specific experiment at the specific time. With this percentage M.A.B. it can be determined if the UAV is successful and even more specific if for example weather circumstances and flying techniques are more successful than others.

To show how this will look like table 3.5 shows already an example of it. For this example is chosen the data of an experiment as was measured on 11^{th} April 2018. During this experiment was decided to fly with a random flight path to see where the higher NO_2 concentration can be detected. Before this random flight experiment the background measurement took place, in which for 5 minutes the air was measured, without an NO_2 emission source emitting NO_2. The table shows the mean of this background measurement, the standard deviation and the confidence level as is decided upon. Together this result in a threshold of 316.69 counts. From the random flight experiment 293 measurement had a higher value as the threshold of the 915 measurements taken. Together this means that during the random flight the measurement percentage M.A.B. was 32%.

To summarize this method it shows the percentage of measurements of all measurements which measured above the background concentration. As this name for this metric is very long, further in this research it will be referred to as percentage of M.A.B., which stands for measurements above background. The percentage of M.A.B. will be used for each separate experiment of the UAV, but as well for calculating the percentage of M.A.B. for the three static sensors.

3.4.2 Data Analysis Method: Interpolation Maps

Next to the use of previous described metric another analysis method will be used during this research. The metric describes the expectation of a percentage of measurements above the background value of NO_2

with 95% certainty, but it does not tell where the concentrations is the highest and how it distributes over space, while the spread of higher NO_2 concentrations over space is the interesting advantage of using a mobile platform instead of static measurement systems. Showing this distribution of measured values over space is done with creating interpolation maps, with the Inverse Distance Weighting interpolation method, further named IDW-interpolation. IDW-interpolation takes the measurement points and interpolates between these measurements, resulting in a raster.

The IDW-interpolation mainly takes distance into account. The closer the raster cell to a measurement point, the more the measurement point influences the interpolated value. The IDW formula used is taken from De Mesnard (2013) and is shown in equation 3.3.

$$\overline{P}_j = \frac{\sum_i^{n_j} = 1 * \frac{1}{d_{ij}^{\alpha}} * P_{ij}}{\sum_i^{n_j} = 1 * \frac{1}{d_{ij}^{\alpha}}} \tag{3.3}$$

In equation 3.3 $\overline{P}_J$ is the estimated value for the specific cell. $\frac{1}{d_{ij}^{\alpha}}$ stands for the inverse of the distance from i to j, where i is the known value of a location and j is the location which needs to be calculated. α is the exponent of the inverse. This estimates how strongly the inverse of distance is executed, in other words it determines how far from the point which is calculated the known points can influence the outcome. The variables used for the IDW interpolation in this research are a cell size of 0.1, using the alpha of 2, and a minimum of 12 points are needed for estimating the interpolation and 40 meters was the maximum distance for taking a point into consideration.

3.5 Experiment Data Pre-processing

Before the data can be analaysed as is explained above, first data preparation has to be done to be able to use the data as gathered by the UAV. The pre-processing is done in several phases.

First it is important to attach height data as was gathered by the UAV to the data as was gathered by the sensor. The sensor gathered height data as well, only this data is not correct, therefore it needs to be combined with the height data as is measured by the UAV itself. Comparing the height data measured by the sensor with the height data as is measured by the UAV itself, the UAV height sensor show that at unexpected moment is measured upto 35m, while the UAV height data show the expected maximum of 12m, which is when flying back to the starting point of measurements. This height data shows exactly what is expected.

The height data can support decision making in how to split up the data in separate experiments. During each flight of around 20 minutes one pattern is flown, but this pattern is repeated several times. For analysis each pattern separate gives the best information about the success of the flying pattern. Therefore the file needs to be split. With the help of the longitude, latitude and altitude data this is possible. The altitude is attached to the sensor data by matching the longitude and altitude patterns as directly attaching is not possible due to different starting times of the UAV and the sensor. Sometimes the starting time is only 9 seconds apart from each other, but in several cases this can go up to 20 seconds. The following steps are the steps undertaken to make to correct decision about the cuts of the data set.

1. Sensor data: recalculate longitude and latitude data from the Degrees, Minutes and Seconds format to Degrees format (DMS to DD format) to match up the format of the UAV data.
2. Sensor data: the time is noted down as real-time from start measurement, transform this into seconds from the start. For example 09:45:38, hour minutes seconds. This turns into 0 seconds. 09:45:39 will become 1 second etc. This matches up the time registration of the UAV data.
3. UAV data: trim the data of the UAV dataset. This is measured each decisecond, but needs to be each second to match up the sensor data. This is done by filtering all the full second measurements out of the data.

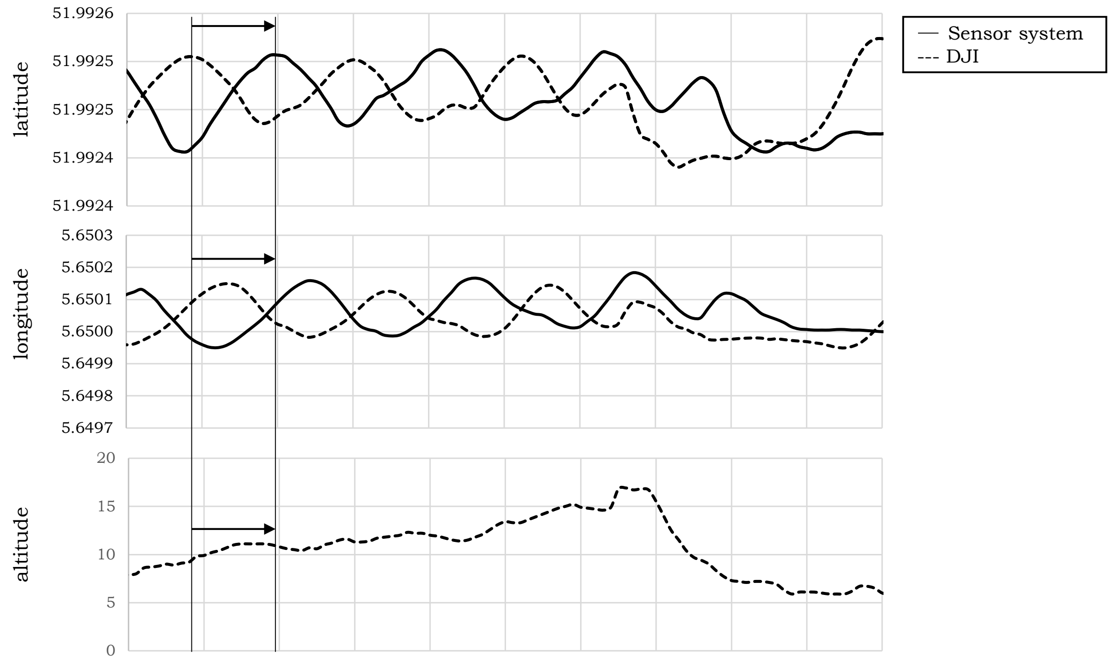


Figure 3.12: The figure shows step 4 of pre-processing. The image first shows latitude, then longitude and at last altitude. The latitude and longitude of the UAV data (DJI) and the UAV sensor data are overlapping, but need to be adjusted until the correct offset is chosen. This offset can be used to connect the correct height with the correct sensor measurements. This figure is a close up of one spiral measurement. This shows in the slowly increasing altitude. When the spiral was done the height fast decreases to start the new spiral.

4. Next the longitude and altitude data of the sensor data and the UAV data will be put together in one graph. The UAV data will be adjusted until the trend matches up with the sensor data. Now it is known which height happened at which moment in the sensor data.
5. With the help of the plots of longitude, latitude and altitude the cuts in the data can be determined. The log-book as was written down during the experiments can help as extra check if the data is cut properly.

What followed out of this pre-processing is that the data has several flaws, sometimes the connection was lost with the UAV, in these parts data is missing. Sometimes the data of the sensor has flaws. By doing this data processing carefully and look to the graphs, a few of this missing gaps could be found and worked around, some other data is missing and not captured during the flight, this will be mentioned in results.

Chapter 4

Evaluation Of The Sensor System: Results

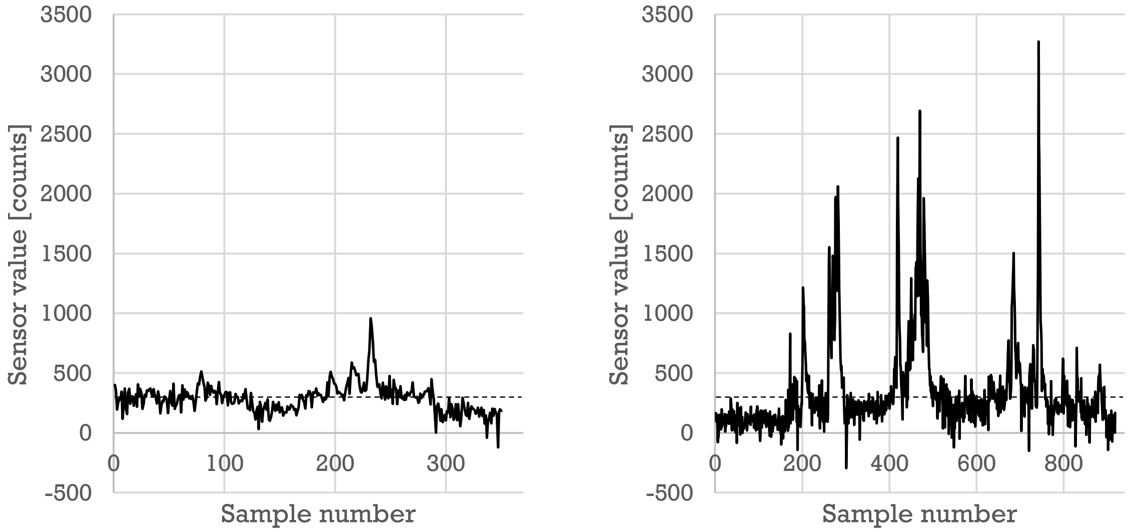
4.1 Results First Measurement Day: Day 0

During the first experiment day there was experimented with several flying styles. First the background measurement was executed, flying the UAV on a fixed spot without the tractor on. Secondly the tractor was put on and on the same fixed spot, 5 meter from the tractor, the emission is measured for 5 minutes. This measurement at a fixed spot, showed a small peak, but not the peak as was expected. Thirdly the UAV was flown in an active flying style. This means that the UAV was constantly flying instead of being at a fixed spot. The flying pattern was random. As can be seen in the figures of 4.1 the flying in a fixed spot, figure 4.1a, showed one small peak, but mainly around the background concentration. The active flying style showed several much higher peaks as can be seen in figure 4.1b. Therefore is concluded that with an active flying style better the highest concentrations of an emission plume can be found. This experiment day helped to design the experiment set-up for the next two measurement days which results will be shown in the following sections.

4.2 Results Different Wind Speeds On Different Measurement Days

In table 4.1a and 4.1b the average percentage M.A.B. of all the executed zigzags and spirals executed on that specific day is shown. The percentage M.A.B. stands for the percentage of measurements which measured a value above the background concentrations. The percentages show how many measurement points during a zigzag are above the background concentration. This is the metric as was explained in this chapter section 3.4.1. The 15^{th} of June has a lowest percentage of 73.0% on average of all the executed spirals on that day and a highest percentage of 99.5%. The 20^{th} of June has a a lowest percentage of 4.8% and a highest percentage of 14.1%. These percentages are shown as well in figure 4.2, in which the averages are shown in bar charts including the error lines. The error lines are calculated by calculating the 95% confidence. Because there is variation in the measurements, the average cannot be known exactly. Therefore a confidence interval is computed, in which the average lies with 95% certainty.

The static sensors show different results between the two days as the UAV sensor showed, the difference between the two days is much smaller and insignificant, which is shown in figure 4.3. The error lines are shown in figure 4.3 as well with the 95% confidence interval in which can be said that the average is a value measured. The uncertainty in the data is very large, going underneath the 0% and above the 100%.



(a) Fixed spot flying (b) Active flying

Figure 4.1: The results of day 0, the first flying day. This day was experiment with the flying style of flying at a fixed point and flying actively. Figure 4.1a showed the results of flying at a fixed points. The counts are concentrated around the background concentration, the dotted line at 333 counts, with one peak detected. Figure 4.1b shows the active flying style, which was random flying around the emission source. In this experiment several high peaks were detected. This result helped gaining insight for the design of the experiments as was executed on the following two measurement days.

Table 4.1: The average percentages of M.A.B. of the performed experiments, as calculated with the metric, for the 3 zigzag experiment repetitions and the 3 spiral experiment repetitions. All heights are included in the average percentages given in the tables below.

(a) 15^{th} of June 2018

Repetition	Zigzag	Spiral
1	79.4%	99.5%
2	77.8%	73.0%
3	78.5%	85.2%

(b) 20^{th} of June 2018

Repetition	Zigzag	Spiral
1	5.1%	14.1%
2	4.8%	7.9%
3	6.0%	8.5%

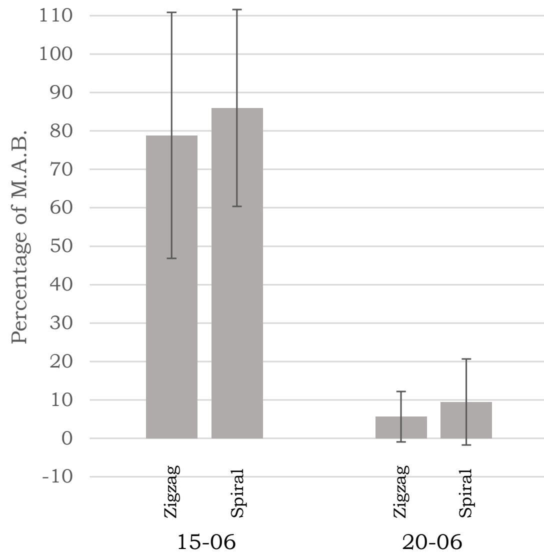


Figure 4.2: A comparison of the average percentage M.A.B. of all heights measured by the UAV sensor between the two measurement days with different wind conditions, and of the two flight methods. The bars indicate the average of the flights, the error bars indicate the 95% confidence interval of the data. A significant difference is observed between the two days, but the difference between the flight methods is insignificant. The confidence intervals being higher than 100% and lower than 0% show high uncertainty and the large spread in the dataset.

These extreme confidence intervals, which are above 100% and lower than 0%, show the large spread in the dataset and the high uncertainty. The 20^{th} of June shows a slightly higher value as the 15^{th} of June, only these results are not significantly different as the uncertainty is so high.

4.3 Results Different Heights

The zigzags have been executed on 3 different heights: 3 meters, 4 meters and 7 meters. As a battery-life was long enough to fly 4 zigzags, the 4 meters zigzag is repeated again. This results of the zigzags on both experiments days are shown in table 4.2a for the 15^{th} of June and in table 4.2b for the 20^{th} of June. On the 15^{th} of June during the second repetition the contact between the sensor and the UAV was lost for the first three zigzags, therefore the data of these zigzags was not stored and only the fourth zigzag at 4 meters could be used from this experiment. On the 15^{th} the minimum value for 3 meters was 69.7% of M.A.B and the maximum value was 81.7% M.A.B. At 4 meters, the minimum was 80.5% and the maximum 98.2%. For 7 meters the minimum was 42.6% and the maximum 69.2%. On the 20^{th} the minimum value for 3 meters was 1.2% and the maximum 9.7%. For 4 meters the minimum was 3.8% and the maximum was 12.7%. For 7 meters the minimum was 2.8% and the maximum 6.6%. On the 20^{th} the first repetition the fourth zigzag is not executed at 4meters, but at 7meters.

On both days there was flown as well with spirals. These spirals started at 3m and ended at 7m. To still be able to say something about the differences in height measured, each flown spiral is split in three equal parts indicated as: low, mid, high. This means that from each spiral all the lower spiral parts are compared with each other, all the middle heights are compared with each other and all the high parts are compared with each other. This resulted in many percentages, too many to show in a table. These values are shown in figure 4.4b and 4.4a. On the 15^{th} the minimum value was in low 65.3%, in mid 58.3% and in high 62.5%. The maximum was in all three categories 100%. On the 20^{th} the minimum was in all

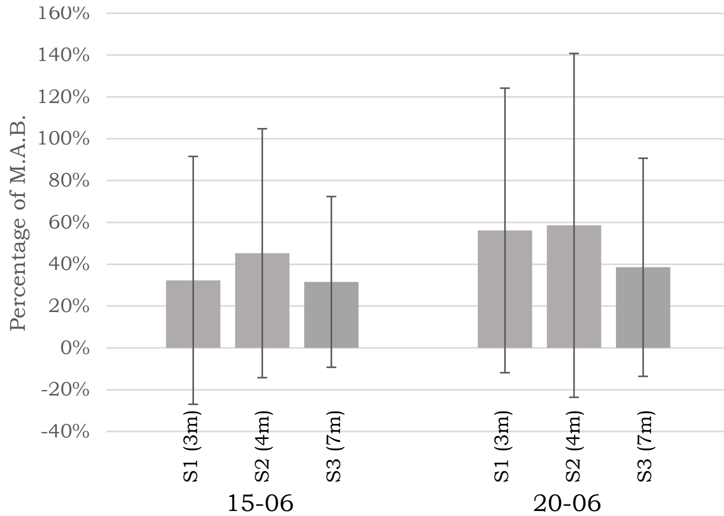


Figure 4.3: A comparison of the average percentage M.A.B. measured by the three static sensors on three different heights, between the two measurement days with different wind conditions. The bars indicate the average of the measurements which measured simultaneously with the period of time the UAV sensor measured, the error bars indicate the 95% confidence interval of the data. Between the two days, the different heights and between the three sensors no significant difference is observed. The confidence intervals being higher than 100% and lower than 0% show high uncertainty and the large spread in the dataset.

three categories 0.0%. The maximum for low was 22.9%, for mid 34.3% and for high 30.8%.

The static sensors show a similar result to the 3m, 4m and 7m as is measured with the zigzag. The 4m has a slightly higher percentage of M.A.B., see figure 4.3. This difference is only not significant, because of the high uncertainty, which is overlapping with the results at 3m and 7m.

In the figures 4.5 and 4.6 interpolation maps are shown of the first zigzag of the 15^{th} and the second zigzag of the 20^{th}. In the description is the height on which the zigzag is flown and the percentage of M.A.B. of the flight. The other interpolation maps are shown in the appendices C for the zigzag IDW maps and D for the spiral IDW maps. Instead of the percentage M.A.B., these interpolation maps show the absolute values measured, because the interpolation is done with the absolute values. So for example when the value measured was 1800 counts, 1800 is shown on the map. A count is the value of the Working Electrode (WE) minus the Auxiliary Electrode (AE). The colours are given by a linear scale and indicate the sensor values. Each of the maps has one middle point, light pink, with higher values, which indicates the higher emission measured.

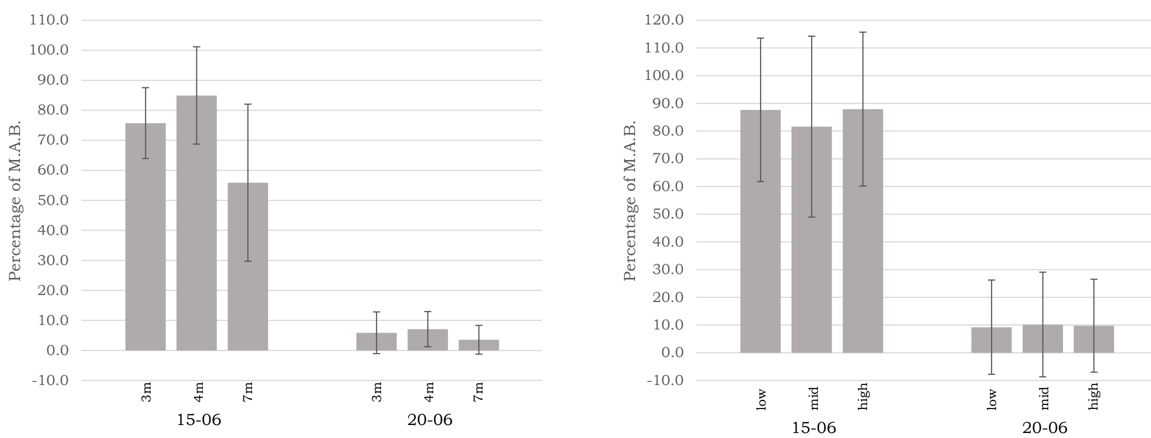
Table 4.2: These tables show the percentage of M.A.B. of the different zigzag experiments splitted per height as is calculated with the metric. The measurements of the 15^{th} of June are in table 4.2a, in repetition 2, the first 3 values are missing, because the connection with the UAV was lost during these zigzags. The measurements of the 20^{th} of June are in table 4.2b, during the firt repetition, the fourth zigzag is not flown at 4m, but at 7m.

(a) 15^{th} of June 2018

Repetition	3m	4m	7m	4m
Zigzag 1:	69.7%	80.5%	69.2%	98.2%
Zigzag 2:				77.8%
Zigzag 3:	81.7%	96.5%	42.6%	93.3%

(b) 20^{th} of June 2018

Repetition	3m	4m	7m	4m	7m
Zigzag 1:	1.2%	12.7%	6.6%		0.0%
Zigzag 2:	6.8%	5.8%	2.8%	7.1%	
Zigzag 3:	9.7%	3.8%	4.8%	6.3%	



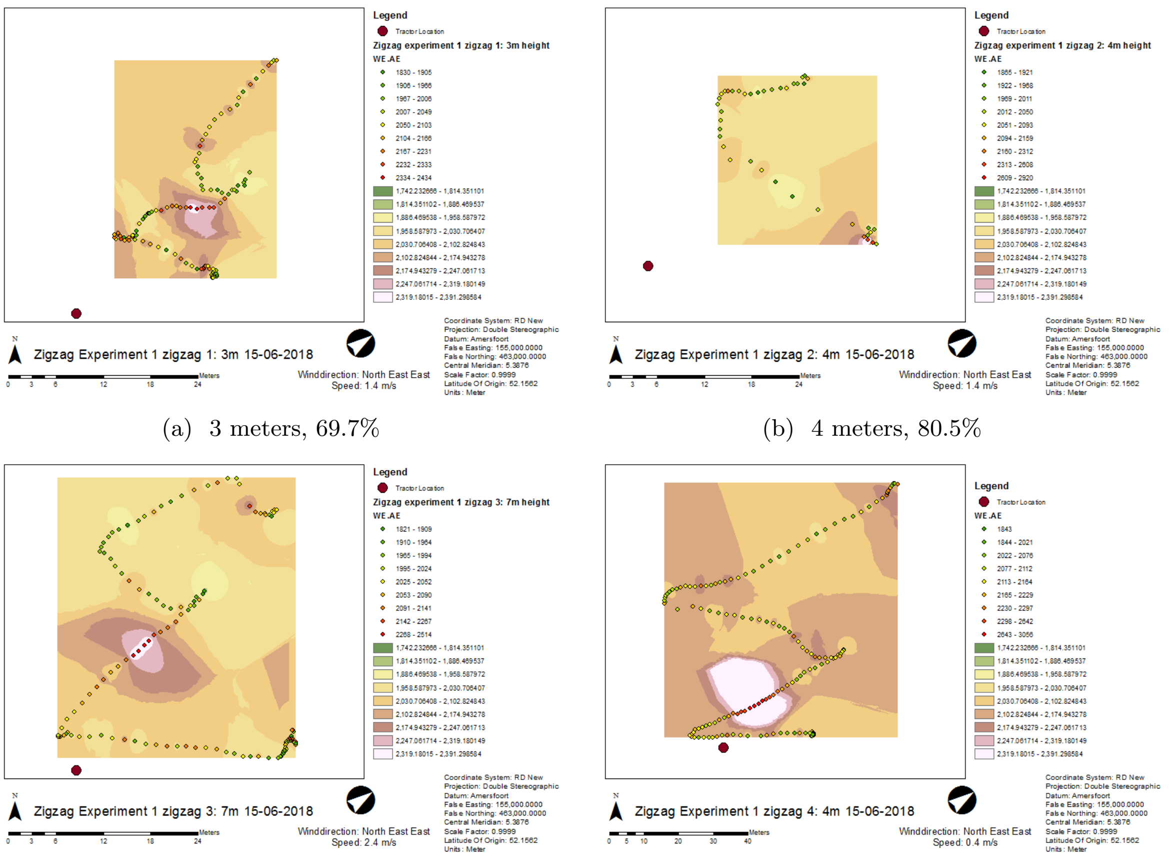
(a) Zigzag (b) Spiral

Figure 4.4: A comparison of the average percentage M.A.B. measured by the UAV sensor between the three different heights, two measurement days with different wind conditions, and of the two flight methods. The bars indicate the average of the flights executed on each height, the error bars indicate the 95% confidence interval of the data. The differences between the three heights are insignificant, as the uncertainty overlaps with each other. The confidence intervals being higher than 100% and lower than 0% show high uncertainty and the large spread in the dataset.

4.4 Results Different Flight Methods

For comparing the flight methods first it is best to look into the averages of all the zigzags and spirals flown. The tables with these values are shown in table 4.1a and 4.1b. On the 15^{th} the lowest value for the spiral was 73.0% of M.A.B. and the highest percentage 99.5%. The zigzag on the 15^{th} was 77.8% and maximum is 79.4%. On the 20^{th} the minimum for the spiral is 7.9% and the maximum 14.1%. The minimum for the zigzag is 4.8% and the maximum 6.0%.

Figure 4.2 shows the bar-plots comparing the different flight methods per measurement day. The spiral results in a higher percentage of measurements measured above background measurement on both days. The bar-plots show the error-lines as well. This indicates the large spread in values and the uncertainty of the measurement. So there is no significant difference caused by the different flight methods.



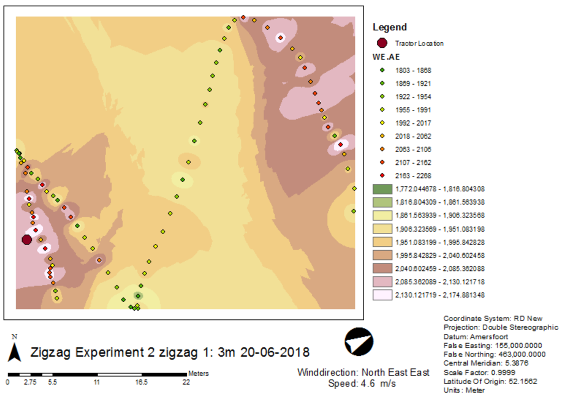
(a) 3 meters, 69.7%

(b) 4 meters, 80.5%

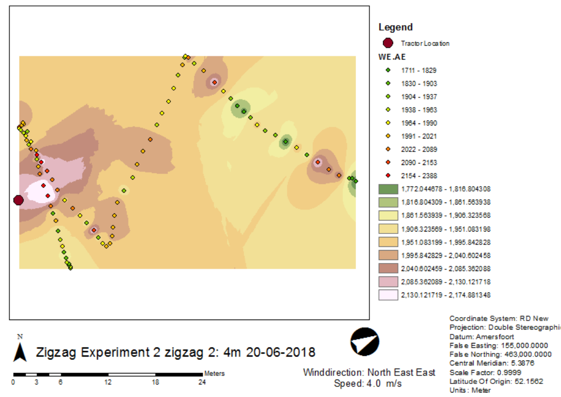
(c) 7 meters, 69.2%

(d) 4 meters, 98.2%

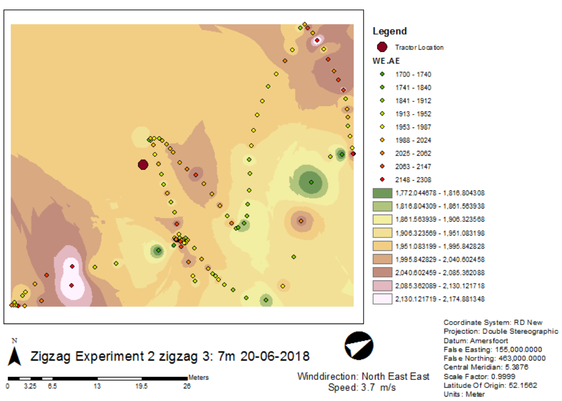
Figure 4.5: A comparison of the interpolation maps of zigzag flight 1 on the 15^{th} of June on 3, 4, 7 and 4m. The maps show the absolute values, which are the counts as is measured by the UAV sensor. The counts are the Working Electrode (WE) signal minus the Auxiliary Electrode (AE) signal. To give an indication what the percentage M.A.B. is calculated for each interpolation map, this value is added in the caption as well as the height at which the zigzag is executed.



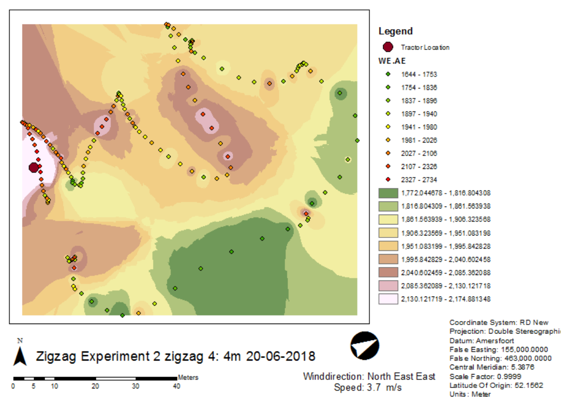
(a) 3 meters, 6.8%



(b) 4 meters, 5.8%



(c) 7 meters, 2.8%



(d) 4 meters, 7.1%

Figure 4.6: A comparison of the interpolation maps of zigzag flight 2 on the 20^{th} of June on 3, 4, 7 and 4m. The maps show the absolute values, which are the counts as is measured by the UAV sensor. The counts are the Working Electrode (WE) signal minus the Auxiliary Electrode (AE) signal. To give an indication what the percentage M.A.B. is calculated for each interpolation map, this value is added in the caption as well as the height at which the zigzag is executed.

Chapter 5

Discussion

5.1 Calibration

5.1.1 Laboratory calibration

The laboratory calibration is in this research experimented with. It was not described extensively before for specific electro-chemical sensors. Therefore this research investigated in a closed gas-box whether the possibility existed to vary enough with the variables of influence on the outcome of the sensor to be able to do the calibration, as described in chapter 3.3. The aim was to use the calibration method from Cross et al. (2017), in which multiple linear regression is used to determine how much each factor, such as temperature, humidity, Working Electrode (WE) and Auxiliary Electrode (AE) are adding to the end result. Eventually this did not work out, as in this research only humidity is varied with.

This was done by using the gas N_2. This gas eliminates all other gases, so the sensor should give a result of no NO_2 emission measured. The temperature was always around 30°C. The humidity could be varied with, now it could be 0% humidity or 60% humidity, by letting the gas first go through a water-box. The calibration could have been completed when is varied with NO_2. However the delivery of pure NO_2 gas took longer than time was available for this research, so with this variable is not experimented.

Having two levels of humidity in the laboratory calibration looks promising because variation in the variables is possible. Interesting would be to vary in temperature in this set-up. Furthermore the main part of this calibration using NO_2 gas, still needs to be experimented with and tested to be sure this calibration method is useful in the future.

5.1.2 Outside calibration

Next to the laboratory calibration, this research experimented with outside calibration. This type of calibration was already executed in the research of Cross et al. (2017). Just as aimed with the laboratory calibration multiple linear regression is used to see how much temperature, humidity, the WE and AE influence the outcome. To do this, the sensor which needs calibration is placed for a week next to a calibrated sensor at a measurement station. This research placed its sensors at the official measurement station of the RIVM in Bilthoven.

Unfortunately taking the results together from the outside calibration it can be concluded that the data at this point was not useful for calibration due to several factors.

1. Measurement location with low to no NO_2 emission

2. Measuring during a warm period, with temperatures over 30°C
3. Measuring during a period with high humidity

The first reason the calibration did not succeed is because there was low to no NO_2 emission. To have a proper calibration several NO_2 points are needed to create a linear correlation through those points to estimate the following points. At this point there is only one NO_2 point: 0. Therefore in the future NO_2 measurements needs to be done closer to emission sources, such as close to a high way. The RIVM has stations there as well, although these are not official stations, the stations have calibrated sensors, so the data can still used for calibration.The second and third point is that the calibration period was too warm and humid, which caused that a large part of the data could not be used ($2/3^{th}$ of the data), because it was exceeding the limits of the sensors.

Several improvements can be made to have better results. First do the calibration in a period when the weather is not warm and humid. This can give a challenge, because it has to be taken into account that the calibration is still close to the moments the sensors are going to be used, because the longer between measurements and the calibration, the more the UAV sensor drifts off and need to be calibrated again. Another option might be to be flexible in time for how long the calibration lasts and take the sensors as soon as there has been a couple days of weather matching the requirements. As this outside calibration method of calibration is already proven by Mijling et al. (2018), the calibration period needs to be taken more time for in the future to succeed.

During the further analysis in this research, no calibration is used, but a metric is developed which show the relative values to its background measurement during the day of measurements. This metric is called percentage M.A.B., which stands for percentage of measurements measured above the background.

5.2 Plume Detection Experiments

After the literature study and the calibration the experiments were executed to test the use of the UAV with the EC sensor in an outside situation. This is done by using two flight methods on several heights between 3 meters and 7 meters. The experiments were repeated two times. The test location was at the premises of Wageningen University and Research and the emission source was the tractor Deutz Fahr DX4.11.SE.

5.2.1 Comparing Different Wind Speeds On Different Measurement Days

The results first looked into the difference between the measurements on the two measurement days, June 15^{th} and June 20^{th}. Figure 4.2 shows that the measurements on both days significantly differ from each other. On the 15^{th} the values were high, while on the 20^{th} the values were low. The difference is even that large, when taking the error into consideration the measured values do not overlap with each other. This all shows that there is a significant difference between those days, having a large impact on the measurements.

Looking into the weather circumstances on the days it shows that the first day the temperature was 4 degrees warmer, 24°C on the 15^{th} and 20°C on the 20^{th} and the humidity was a bit lower, 70% and on the 20^{th} 79%. The largest difference is the difference in wind speed: on the 15^{th} the wind speed was much lower, between 0.0m/s to 2.9m/s, while on the 20^{th} the wind speed was between 2.1m/s and 5.3m/s. This is expected as in the literature study on plume detection showed that wind influences the measurements, as for example Neumann et al. (2013) showed. As in literature the influence of wind is named and the temperature and humidity differ relatively little, the wind shows as the most likely reason for the differences.

The static sensors show at first sight a complete opposite trend. The values of the second measurement day are slightly higher than the values of the first measurement day. However this trend is not significant

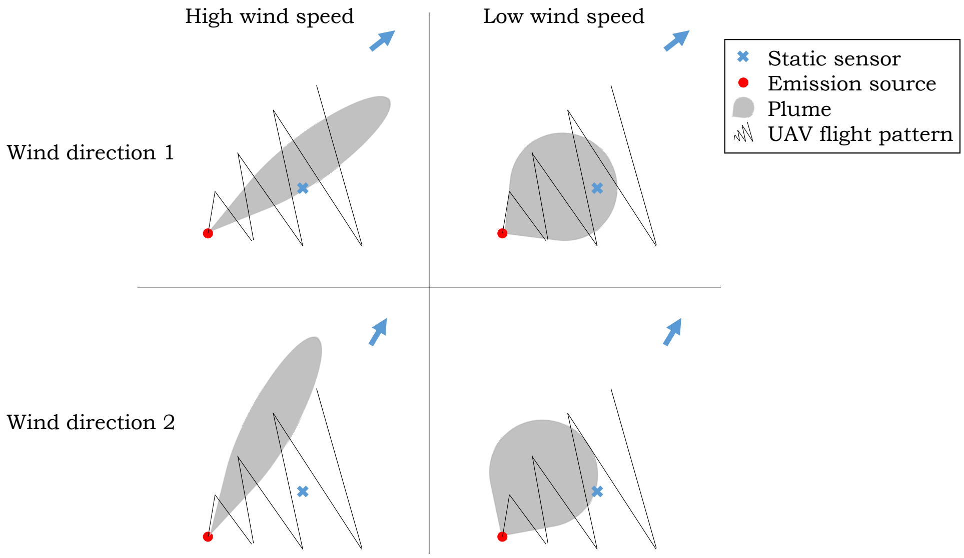


Figure 5.1: Visualization of a suggested cause of the high uncertainty in the static sensors and the low percentage M.A.B. on the high wind speed day for the UAV sensors. During the high wind speeds, the NO_2 plume is more narrow, which causes that the UAV flies shorter through the plume. During low wind speeds, the plume is more wide, such that the UAV has longer flying time in the plume. The static sensors are, depending on subtle changes in wind direction, either completely in the plume or completely out, at high wind speeds as well as at low wind speeds. Therefore on both days there is high uncertainty, having values differing from 0 to 100% M.A.B.

as the error lines of both days are overlapping and show the high uncertainty. Therefore there is a clear difference between the static sensors and the UAV sensor, as the static sensors have much more uncertainty. A suggested cause of this difference is the influence of the wind on the NO_2 plume, visualized in figure 5.1. On the day with the high wind speed, the plume gets more narrow. During the measurements there will be small wind direction changes, represented in figure 5.1 as wind direction 1 and 2. The UAV flies a short amount of time through this plume, giving low percentage of M.A.B., while during the low wind speed day the UAV flies for a longer amount of time through the NO_2 plume, resulting in higher percentages of M.A.B. The static sensor is on both days depending on wind direction either in the plume, having high percentage of M.A.B. or out of the plume, having a very low percentage of M.A.B. The large variation in percentage M.A.B. are visible in the graph in the bar plots in the appendix B, figure B.2.

Although there are strong signs that the data between the two days differ, because of wind, some improvements in the experiment set-up can be made to make sure that this is the case. For example, now the only moment the UAV flew without the source emitting NO_2 was during the background measurements in the beginning. When next to this background measurement the UAV flew the two patterns repeatedly, the results can be compared to the measurements when the UAV is emitting NO_2. Expected is that these values show 0% emission from the background concentration.

From the results it becomes clear that the measurement day had a significant effect on the outcome. The second measurement day, June 20^{th} having higher wind speeds: a minimum measured from 2.1m/s and a maximum of 5.3 m/s, while June 15^{th} had a minimum of 0.0m/s and a maximum of 2.9m/s. This gives the indication that wind is a large influence factor, making it more difficult for the UAV to find the plume.

5.2.2 Comparing Heights

At first sight the zigzag shows higher values at 4m height at both days, as it has higher peaks than the values on 3m and 7m. This can be an indication that NO_2 is more present at 4m height. This can be possible as the emission is emitted by the tractor at a height of 3m. However, the differences are insignificant due to the large variation in the dataset. Values measured for each height level have such a large spread, that their confidence intervals overlap between the 3 height differences. This means that within the zigzag pattern no significant difference is measured between the three heights.

The spiral pattern shows a similar pattern between the different heights as the zigzag. The spread in values is large, causing overlapping confidence intervals between the three height groups, low, mid and high. This means that within the spiral pattern no significant difference is measured between the three heights.

The static sensors show the same higher values at 4m height on both days as the UAV does in both patterns. However, this difference is not significant. The results of 3m, 4m and 7m have overlapping confidence intervals.

One reason to explain the insignificant differences has to do with the difference in wind speed as is described in section 5.2.1. The variation caused by wind speed is so large, the small differences due to height are overruled by the differences created by wind speed.

Secondly, Roldán et al. (2015) and Villa et al. (2016b) suggest another cause for insignificant differences in height: they describe the rotor wind might influence the measurements. The rotors of the UAV pull in wind from above and push it to ground and therefore might mix the air of different heights. This explanation needs to be researched further.

The interpolation maps, in the figures in appendices C and D, show additional proof that the wind influences the measurements. Looking into the map no clear trend can be detected. Often high values are detected close to the emission source, but as well at seemingly random locations. This shows that the wind spreads the emission NO_2 over space.

Furthermore it is not immediately clear from the figures which measurements are above background concentration. For future research, interpolation maps with two colours can be made, showing higher or lower than a specified concentration. This can be the background concentration, or, when in future research the calibration has been successful, the interpolation can be made in $\mu g/m^3$. This way the maps can be compared with standards giving an indication when the concentration NO_2 is air pollution.

5.2.3 Comparing Flight Methods

Shown in figure 4.2 the spiral flight method has on both measurement days a slightly higher result, but this effect is not significant. The spread in the dataset is that large in the spiral dataset, that it overlaps with the results of the zigzag dataset. The lack in difference show that the influence of the weather data is larger than the effect of flight method chosen.

Interesting to see is that the static sensors do not change during the two different weather circumstances. The static sensors still measured NO_2 on the second windy day. As explained in the wind section in section 5.2.2, this is probably because the static sensors are at the same place, which causes that it is able to catch the NO_2 always as soon as it is flown towards the static sensors. The UAV has with its flight patterns more difficulty finding this fast changing NO_2 plume, as it is fast moving itself. This indicates that when the UAV is going to be used more advanced flight patterns are necessary to be able to have the same results as the static sensors.

The design of the flight methods is based on literature. As gas sensors mounted on a small UAV is a relatively new topic in research, just a few examples were available with flight methods used. Therefore examples were used of articles with flight methods designs for airplanes. Mainly these used the zigzag flight method. Within the larger UAVs the spiral was used. All used manual flying. Only Neumann et al. (2013) experimented with programmed algorithms which determined the flight path. From above it became clear that there was no specific difference between the flight methods, which one was better. Both flying methods were able to detect some emission, but the result is not convincing. Expected is that this is exactly due to what Neumann et al. (2013) tried to tackle. The emission plume flows in general in the wind direction, but is very susceptible to small changes in wind. This is what the interpolation maps show as well in figure 4.5 and 4.6. In general most emission is detected close the emission source, but there are areas spread over the research area where higher emission get detected. These small areas of higher emission can be brought there by subtle changes of the wind, spreading the emission over a larger area than just in the dominant wind direction. As it is very hard to adjust the flight method to these subtle wind changes manually as this is not measurable at the ground. Therefore it can be supportive as the UAV is able to make choices themselves in flight path. Neumann et al. (2013) called it Gas Source Localization (GSL).

Another field in research developing algorithms for this is so-called *infotaxis*. Infotaxis is based on chemo-taxis, which is the phenomenon that organisms move based on the gradient of chemicals. Infotaxis takes more information into consideration, which makes that these gas gradient decisions can be made in areas where sparse information. Eggels et al. (2017) made simulations in 3D using this infotaxis algorithm. The algorithm was able to react on the fast and subtle changes of air. This is interesting to keep in mind for future research, as UAV time can be optimized for its goal: finding and measuring the emission. What is interesting is that Eggels et al. (2017) found that the flight path results often in a zigzag pattern perpendicular to the wind. This is reassuring that the chosen flight method zigzag is not optimal, but it is a realistic flight path to follow.

Chapter 6

Conclusion

6.1 Sub-question 1: Literature study

In chapter 2 the aim was to be able to answer the first sub-question by doing a literature study. The question and answer will follow below.

Sub-question 1 *What is known in literature about the development and use on electro-chemical sensor mounted to a UAV?*

From chapter 2 it becomes clear that the research to air quality with UAVs was researched before, but still at the start of developments on this topic. The first literature written on this topic is written by Pobkrut et al. (2016); Neumann et al. (2013); Villa et al. (2016b); Roldán et al. (2015). These researches were are the start of developments, still it did not give a full understanding how the UAV with the sensors could be used in an outside situation and measure the air pollution, as Villa et al. (2016b) measured at one place inside a large hall and Roldán et al. (2015) focused on research in a greenhouse. Therefore the literature study used other articles in which large UAVs were used and in which air quality was researched with airplanes.

An advantage of using small UAVs instead of large UAVs or airplanes, is the amount of regulation around it. For an airplane an airfield is needed, a pilot and the possibility to fly in the area with an airplane. Large UAVs, such as the fixed wing UAV used in the research of Peng et al. (2015) or the helicopter UAV used in Khan et al. (2012), have the advantage that it can be launched from the research location, but still a license is needed. The last category, the small UAV, which are in the Netherlands, UAVs lighter than 4kg which may fly in areas upto 100m from the pilot, no license is needed, or when used professionally a light-license is needed (Rijksoverheid, 2017). This give possibilities for easier research of air pollution and to get closer to emission sources interested in. When UAVs get smaller, the detection system needs to be smaller as well, otherwise the UAV is not able to carry the weight. This means smaller sensors.

In this research four types of sensors are discussed: Laser based sensors, particle counters (PC), metal-oxided sensors (MOX) and electro-chemical sensors (EC). The MOX and EC sensors are the smaller sensors, therefore these are especially useful for the small UAVs. Bhoga and Singh (2007) reviewed the development of these EC sensors and it looked promising as they have a quick response time, are small, affordable and the development of the sensors continues. The downsides of the EC sensor is the cross-sensitiveness, influence of temperature and the influence of humidity. These factors introduce noise on the signal.

That the EC sensors are relatively new sensors used on the small UAV still raises some questions. Some first studies show the potential, but upto now show some contradictories as well. The first contradictory point is the sensor location on the UAV. Villa et al. (2016b) proposes a system with a 1m beam outside the UAV. This way the sensors are not influenced by the air disturbance of the UAV rotors. However, this system is not applicable in an outside situation, as it is too heavy and makes the UAV in unbalance. Roldán et al. (2015) proposes to put the sensors on top of the UAV, but this requires some more elaborate study in which the influence of the wind created by the rotors on the UAV is shown. Another topic of research interesting is the use of a gas-tube to place the sensors in. At this point this technique is used in the Particle Counters sensors, but might be interesting for the EC sensor as well, as within a tube the wind disturbance is less.

Calibration is another topic of discussion. At this moment, researchers often use manufacturers calibration. Research of Jiang (2018) has shown that further calibration is necessary as the sensor has the tendency to drift off after a period of time. This calibration can be used more and more extensively in other research. Further research can even research more the influence of wind on the sensors and this can have a potential to be added to the calibration as well.

The influence of the wind is not only from the rotors, but the main wind influence is from the wind of the environment as wind direction outside changes quickly and can be strong. This means that strategies are necessary to find the emission to measure. Within this literature study flight methods from airplanes are analyzed and especially the zigzag pattern is used a couple times, such as in Berg et al. (2012). Neumann et al. (2013) proposed a system for UAVs that is able to automatically find the emission source. This can be research and studied further as at this point it is not user friendly and easily available. Next it will be interesting to take altitude into consideration as well.

To conclude with the answer to the first sub-question, at this moment little is known about the use of an electro-chemical sensor mounted to a UAV measuring in an outside situation. For understanding which flight path could be useful, articles with other UAV sensor combination or airplanes were helpful to understand that zigzag and spiral are suited flight paths. Research specific on the electro-chemical sensor has shown that calibration of the sensor is important. Nevertheless more research on the specific NO_2 electro-chemical sensor mounted to a UAV is useful, as there is no consensus on which location the sensor should be mounted to the UAV, and can be researched further for the specific use for outdoor measurements.

6.2 Sub-question 2: Experiment

In chapter 3 to chapter 5 the aim was to answer the second sub-question by executing experiments in an outside situation. The question and answer will follow below. The sub-question will be answered in three parts: wind, heights and flight method. Before these three parts are answered, first is looked into laboratory and outside calibration as this was a large research part determining the analysis method with %-M.A.B.

Sub-question 2 *What is the influence of wind speed, height of the measurements and flight method on the measured NO_2 with the measurement system?*

6.2.1 Calibration

During the calibration two types of calibration have been experimented with: laboratory calibration and outside calibration.

Laboratory calibration

The laboratory calibration was executed in a laboratory and experimented with for the first time. It had to be tested if the temperature, humidity and amount of NO_2 could be varied with. Varying with humidity was possible by letting the gas first go through a water-box, before it entered the gas-box.

Temperature was harder to vary with as it was in the gas-box always around 30°C, which is too warm for the sensors. For varying in temperature new solutions have to be found. Varying in NO_2 in the calibration is not taken into consideration, but is advised to do so in the future as it will provide a better calibration result. When laboratory calibration is further experimented with it can be a quicker solution than the outside calibration, as the sensors do not have to be for a week outside. Next there will be no dependency anymore on the changing weather circumstances outside, because temperature and humidity can be changed manually in the laboratory.

Outside calibration

The outside calibration was executed at the official measurement station of the RIVM in Bilthoven. After the calibration week, the result did not show correlation between the parameters, because the measurements were influenced by high temperatures, more than 30°C, high humidity, more than 90% and low amount of NO_2, as the measurement location was in a forest area. For further use of this type of calibration it is advised to:

1. Measure on a location with a lot of NO_2 emission variation, such as the highway
2. Measure during a period with temperature between 5°C and 25°C
3. Measure in a period with varying humidity, so a week with some light rain, but dry periods as well

To still be able to compare the results without calibration a metric has been developed which takes the background measurement and calculates the percentage of measurements which measured higher as the background measurement: percentage of measurements measured above the background, %-M.A.B. This method makes it possible to compare the measurement days, the several flying heights and the flying methods.

6.2.2 Wind

What is the influence of wind speed on the measured NO_2?

The wind speeds has a significant effect on the measurements. During the day with low wind speeds, maximum 2.9m/s, the percentage of M.A.B. was significant higher as on the day with high wind speeds, maximum 5.3m/s. Therefore it can be concluded that flying with low wind speeds will give better measurement results.

Secondly, when combining the measurements from the UAV sensor data with the static sensors, the sensors showed a different trend. The static sensors show on both days a similar trend, while the UAV sensors show a significant differences. Expected is that the shape of the plume is influenced by the wind speed as shown in figure 5.1. Together with the subtle changes of wind direction the static sensors change constantly of being in the plume and out the plume. This happens similar on a low wind speed day as on a day with high wind speed. The UAV sensor is more influenced by this change of shape as with a more narrow shape during high wind speed days, the flying time of the UAV in the plume is shorter giving a low %-M.A.B. as result.

It can be concluded that the wind has a large influence on the measurements. Flying with wind speeds under 2.9m/s give a higher %-M.A.B. Furthermore it is expected that the wind influences the shape and specific location of the plume giving more difficulty to fly in the plume.

6.2.3 Heights

What is the influence of measurement height on the measured NO_2?

Flying on different heights does not show significant differences. From this can be concluded that several heights around the emission source can be used.

6.2.4 Flight method

What flight method is most suited to find the NO_2 plume?

Comparing the two flight methods, spiral and zigzag, there is no significant differences between both methods. Therefore can be concluded that the flying method is not of large influence and both methods can be used. The expectation is that improvements on the flying method can be made when using more automatized flying methods such as Gas Source Localization (Neumann et al., 2013) or Infotaxis (Eggels et al., 2017), as these methods focus on following the plume, there is a higher probability of flying within the plume. These automatized can help to deal with the effect on wind on the measurement.

6.3 Main Question

Main question *Is it possible to characterize an NO_2 plume with an NO_2 electro-chemical sensor mounted to a UAV?*

Taking the two sub-questions into consideration it can be concluded that it is possible to detect an NO_2 plume with an NO_2 electro-chemical sensor mounted to a UAV. However, characterizing is at this moment one step to far. For characterizing it is useful to know how the plume behaves more precisely. This can be achieved by, as sub-question 1 describes, improve the knowledge on the sensor location on the UAV and do more research to the behaviour of the sensor UAV combination outside.

That characterizing at this moment is one step to far can as well be concluded from sub-question 2. The second sub-question experimented with characterizing the NO_2 plume outside by looking into the influence of wind, comparing different flying heights and comparing the flight methods. From this can be concluded that the wind has a large influence on characterizing the NO_2 plume, the harder the wind the harder it gets to characterize the plume. Within this research the best results were obtained by flying with a maximum wind speed of 2.9m/s. What the influence is from height and flight method is uncertain, no significant differences have been found between the different measurement heights and flying methods.

For the future it can be possible to look into the sensor location on the UAV, to find the ideal location on the UAV. Secondly the calibration of the sensors is important to study further as well. When laboratory calibration is studied further a quicker calibration is possible. Furthermore extending the flight methods can be interesting, to look into the possibility of using algorithms, such as the Gas Source Localization or Infotaxis. When the possibility exists to use such an algorithm, again the influence of wind is an interesting topic to look into again, as it is possible that with slightly faster wind speeds, NO_2 detection is still possible.

Chapter 7

Recommendations

For further research I would recommend to certainly continue this research and continue this promising combination of electro-chemical sensor and UAV. What I recommend to do more research in is listed below. The four points are the points I had to deal with most often:

1. Further research on the sensor location on the UAV, especially because research is at this point contradictory. This also corresponds with the effect of wind from the UAV rotors, as the best location on the UAV, is the location with the less influence of the UAV rotors.
2. Further research in the topic of calibration. The calibration in the lab can be extended and experimented with more as with this method dependency on specific weather for calibration is less. New methods have to be thought of to vary the temperature as well in the gas-box before this can be used.
3. When laboratory calibration will succeed, laboratory experiments can be conducted in which the influence of wind is experimented with in the gas-box. This might be done in a gas-box as used in this research, but with as well a controlled inflow and outflow for wind. When this succeeds and a correlation can be found, this can be tested as well outside.
4. Use when experimenting outside automated flight system with Gas Source Localization (Neumann et al., 2013) or Infotaxis (Eggels et al., 2017). This way it is easier to respond to sudden changes of the wind direction and fly more in the plume.

The last recommendation, recommendation 4 is an important recommendation as my expectation is that it has the potential to improve the results a lot. Due to the effect of wind and the characteristics of gas, gas spread fast and unpredictable over the area and makes it harder to find. With this system the finding can go faster and more precise. Recommendation 3 goes further into the research of the wind effect on measuring. When the wind effect is understood properly, advice can be given upto which wind speeds can be flown or new tactics can be thought of to deal with the effect of wind. As well I recommend to look into laboratory calibration. This type of calibration can be helpful as the weather outside can change a lot in a period of 5 days, it can be hard to have the weather circumstances hoping for. The laboratory calibration can be quicker and can always be executed.

Bibliography

Airparif (2017). Airparif - association de surveillance de la qualité de l'air en Île-de-france.

Alphasense (2017). Welcome to alphasense.

Anderson, H. R. (2009). Air pollution and mortality: A history. *Atmospheric Environment*, 43(1):142–152.

Berg, N., Mellqvist, J., Jalkanen, J., and Balzani, J. (2012). Ship emissions of so2 and no2: Doas measurements from airborne platforms. *Atmospheric Measurement Techniques*, 5(5):1085–1098.

Berman, E. S., Fladeland, M., Liem, J., Kolyer, R., and Gupta, M. (2012). Greenhouse gas analyzer for measurements of carbon dioxide, methane, and water vapor aboard an unmanned aerial vehicle. *Sensors and Actuators B: Chemical*, 169:128–135.

Bhoga, S. and Singh, K. (2007). Electrochemical solid state gas sensors: An overview. *Ionics*, 13(6):417–427.

Breuninger, C., Oswald, R., Kesselmeier, J., and Meixner, F. (2012). The dynamic chamber method: trace gas exchange fluxes (no, no 2, o 3) between plants and the atmosphere in the laboratory and in the field. *Atmospheric Measurement Techniques*, 5(5):955–989.

Cox, L. and Blaszczak, R. (1999). *Nitrogen oxides (NOx) why and how they are controlled*. DIANE Publishing.

Cross, E. S., Williams, L. R., Lewis, D. K., Magoon, G. R., Onasch, T. B., Kaminsky, M. L., Worsnop, D. R., and Jayne, J. T. (2017). Use of electrochemical sensors for measurement of air pollution: Correcting interference response and validating measurements. *Atmospheric Measurement Techniques*, 10(9):3575.

De Mesnard, L. (2013). Pollution models and inverse distance weighting: Some critical remarks. *Computers & Geosciences*, 52:459–469.

Eggels, A., Kunnen, R., Koren, B., and Tijsseling, A. (2017). Infotaxis in a turbulent 3d channel flow. *Journal of Computational and Applied Mathematics*, 310:44–58.

Eller, A. S. and Sparks, J. P. (2006). Predicting leaf-level fluxes of o3 and no2: the relative roles of diffusion and biochemical processes. *Plant, cell & environment*, 29(9):1742–1750.

EuropeanCommission (2011). White paper 2011 - mobility and transport - european commission.

Fahlstrom, P. and Gleason, T. (2012). *Introduction to UAV systems*. John Wiley & Sons.

FMI (2018). How does weather affect air pollution?

Friedlander, S. K. (1973). Chemical element balances and identification of air pollution sources. *Environmental Science & Technology*, 7(3):235–240.

Jiang, Q. (2018). *Citizen Sensing for Environmental Information.* dissertation, Wageningen University and Research.

Jiang, Q., Kresin, F., Bregt, A. K., Kooistra, L., Pareschi, E., Van Putten, E., Volten, H., and Wesseling, J. (2016). Citizen sensing for improved urban environmental monitoring. *Journal of Sensors*, 2016.

Khan, A., Schaefer, D., Tao, L., Miller, D. J., Sun, K., Zondlo, M. A., Harrison, W. A., Roscoe, B., and Lary, D. J. (2012). Low power greenhouse gas sensors for unmanned aerial vehicles. *Remote Sensing*, 4(5):1355–1368.

Kim, H., Song, C., Park, R., Huey, G., and Ryu, J. (2009). Investigation of ship-plume chemistry using a newly-developed photochemical/dynamic ship-plume model. *Atmospheric Chemistry and Physics*, 9(19):7531–7550.

Klein, J. and Fortuin, P. (2014). Task force on transportation of the dutch pollutant release and transfer register. *CBS*.

KNMI, ESA, and DUP (2017). General introduction of temis.

Kurtenbach, R., Vaupel, K., Kleffmann, J., Klenk, U., Schmidt, E., and Wiesen, P. (2016). Emissions of no, no 2 and pm from inland shipping. *Atmospheric Chemistry and Physics*, 16(22):14285–14295.

Luchtmeetnet (2017). Luchtmeetnet.

Malaver, A., Motta, N., Corke, P., and Gonzalez, F. (2015). Development and integration of a solar powered unmanned aerial vehicle and a wireless sensor network to monitor greenhouse gases. *Sensors*, 15(2):4072–4096.

Mijling, B., Jiang, Q., Jonge, D. d., and Bocconi, S. (2018). Field calibration of electrochemical no 2 sensors in a citizen science context. *Atmospheric Measurement Techniques*, 11(3):1297–1312.

Neumann, P. P., Bennetts, V. H., Lilienthal, A. J., and Bartholmai, M. (2016). From insects to micro air vehicles—a comparison of reactive plume tracking strategies. In *Intelligent Autonomous Systems 13*, pages 1533–1548. Springer.

Neumann, P. P., Hernandez Bennetts, V., Lilienthal, A. J., Bartholmai, M., and Schiller, J. H. (2013). Gas source localization with a micro-drone using bio-inspired and particle filter-based algorithms. *Advanced Robotics*, 27(9):725–738.

Nunnermacker, L., Weinstein-Lloyd, J., Hillery, B., Giebel, B., Kleinman, L., Springston, S., Daum, P., Gaffney, J., Marley, N., and Huey, G. (2008). Aircraft and ground-based measurements of hydroperoxides during the 2006 milagro field campaign. *Atmospheric Chemistry and Physics*, 8(24):7619–7636.

Patterson, M., Mulligan, A., Douglas, J., Robinson, J., and Pallister, J. (2005). Volcano surveillance by acr silver fox. *Infotech@ Aerospace*, page 6954.

Peng, Z.-R., Wang, D., Wang, Z., Gao, Y., and Lu, S. (2015). A study of vertical distribution patterns of pm 2.5 concentrations based on ambient monitoring with unmanned aerial vehicles: a case in hangzhou, china. *Atmospheric Environment*, 123:357–369.

Pobkrut, T., Eamsa-ard, T., and Kerdcharoen, T. (2016). Sensor drone for aerial odor mapping for agriculture and security services. *IEEE*, pages 1–5.

Rijksoverheid (2017). Welke vergunning heb ik nodig voor mijn drone?

Riley, E. A., Schaal, L., Sasakura, M., Crampton, R., Gould, T. R., Hartin, K., Sheppard, L., Larson, T., Simpson, C. D., and Yost, M. G. (2016). Correlations between short-term mobile monitoring and long-term passive sampler measurements of traffic-related air pollution. *Atmospheric Environment*, 132:229–239.

RIVM (2017). No2 concentratie 2016 zipbestand.

Roldán, J. J., Joossen, G., Sanz, D., del Cerro, J., and Barrientos, A. (2015). Mini-uav based sensory system for measuring environmental variables in greenhouses. *Sensors*, 15(2):3334–3350.

Stella, P., Kortner, M., Ammann, C., Foken, T., Meixner, F., and Trebs, I. (2013). Measurements of nitrogen oxides and ozone fluxes by eddy covariance at a meadow: evidence for an internal leaf resistance to no 2. *Biogeosciences*, 10(9):5997–6017.

Villa, T. F., Gonzalez, F., Miljievic, B., Ristovski, Z. D., and Morawska, L. (2016a). An overview of small unmanned aerial vehicles for air quality measurements: Present applications and future prospectives. *Sensors*, 16(7):1072.

Villa, T. F., Salimi, F., Morton, K., Morawska, L., and Gonzalez, F. (2016b). Development and validation of a uav based system for air pollution measurements. *Sensors*, 16(12):2202.

Weber, K., HEWELING, G., FISCHER, C., and LANGE, M. (2017). The use of an octocopter uav for the determination of air pollutants–a case study of the traffic induced pollution plume around a river bridge in duesseldorf, germany. *International Journal of Environmental Science*, 2:63–68.

WHO (2006). Who challenges world to improve air quality.

WHO (2016). Who global urban ambient air pollution database (update 2016).

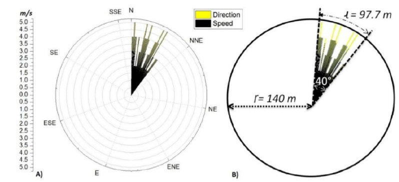
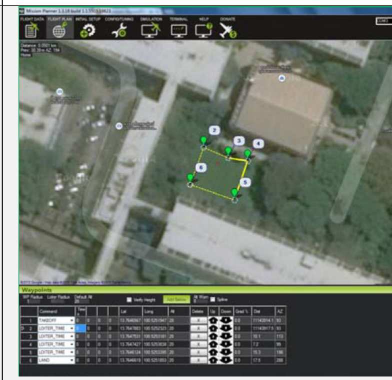
WHO (2017). Air quality guidelines - global update 2005.

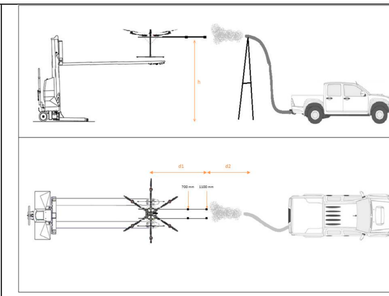
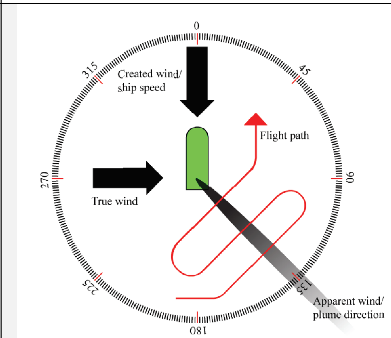
Appendix A

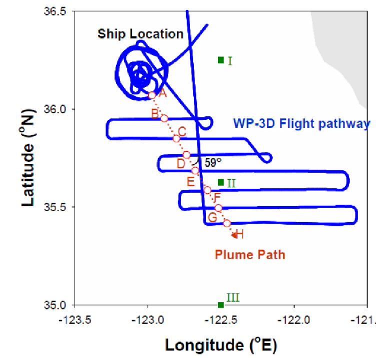
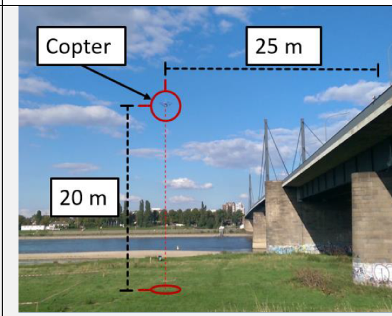
Literature Tables

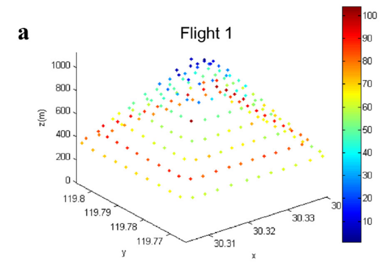
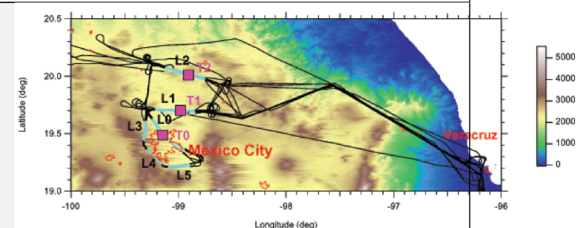
In table A.1 an overview is given what literature within the work field of measuring air quality with UAVs and airplanes specific on ships as well as in general and the working field of measuring gases with a UAV is described what flight plans they were handling during their experiments. Within 2 section 2.5 this table is used to describe how path planning has be done upto now. In chapter 3 section 3.2 the table is used to develop a flight plan for the experiments.

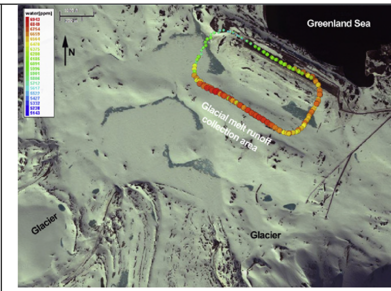
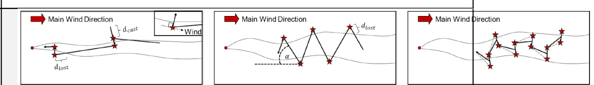
Table A.1: Literature review table giving an overview on the flight plans used in several researchers, focussing on air quality, air quality around ships or gas sensing with UAVs. In the column Equipment FW stand for Fixed Wing UAV

Author	Year	How Plume	Height	Cover area	repetition	Time	Speed	Equipment	Image
Khan	2012	No plume, general amount air	-	-	-	-	-	T-Rex helicopter	
Malaver	2015	Circular	0-50m ASL	radius 140m	-	50-10min	12.6m/s	FW solar	
Pobkrut	2016	Square in wind direction	15m	1.5m x 1.5m	-	20min	0 m/s	Quadcopter	

Villa	2016	Static	3m = emission height	0m2	-	12-13min	0m/s	Hexa-copter	
Berg	2012	Zigzag perpendicular	290 and 150m ASL	52 ships, 160 measurements	3 days and 7 days	hours	50 m/s and 35 m/s	Airplane	

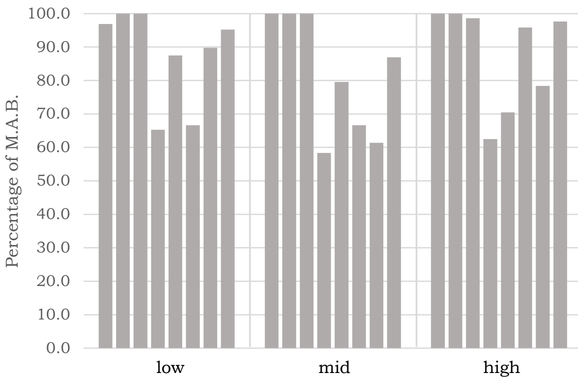
Kim	2009	Zigzag 59degrees + circular around ship	800m ASL	160 x 200km	8x in one day	hours	360 km/h	Airplane	
Weber	2017	Climb in 3 steps at 3 points	15-30m (bridge was at 15m)	15m, 25m, 35m from bridge	60x	20min	0m/s	Octocopter	

Peng	2012	Squared spiral increasing in height	300m - 700m	16km2	6 days 22 flights	15min	-	FW petrol	
Nunner - macker	2008	Random in wind direction, transect several plumes of industry	500-2500, 2500-3500, 3500-4000	large area	-	-		Airplane	

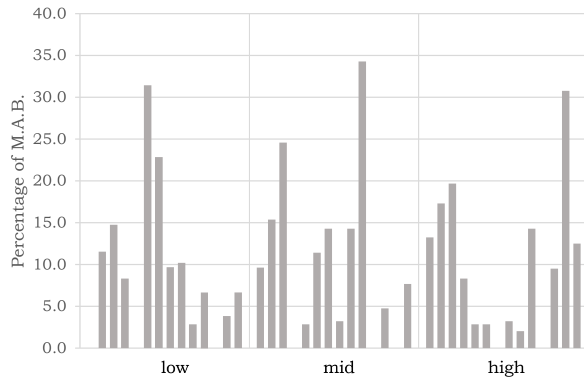
Berman	2012	Race track shaped path, no plume general amount air	10m water vapour, but upto 3500m ASL	few km	8x in 1 flight	25min	28m/s	FW petrol	
Neu-mann	2013/ 2016	3 algorithms: surge-cast , zigzag, pseudo-gradient	source emission height	20x16m	-	-	-	Quad-copter	(a) Surge-Cast Algorithm (b) Zigzag Algorithm (c) Pseudo Gradient-based Algorithm

Appendix B

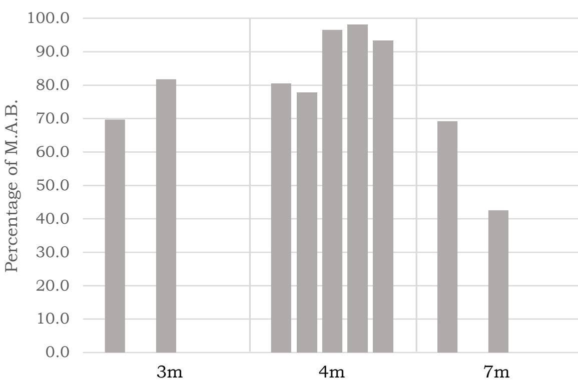
M.A.B. results



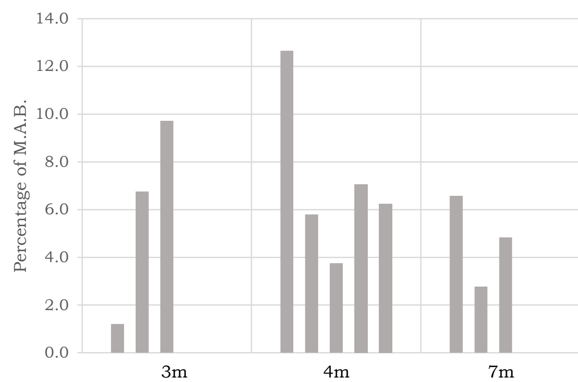
(a) 15^{th} June 2018 spiral



(b) 20^{th} June 2018 spiral

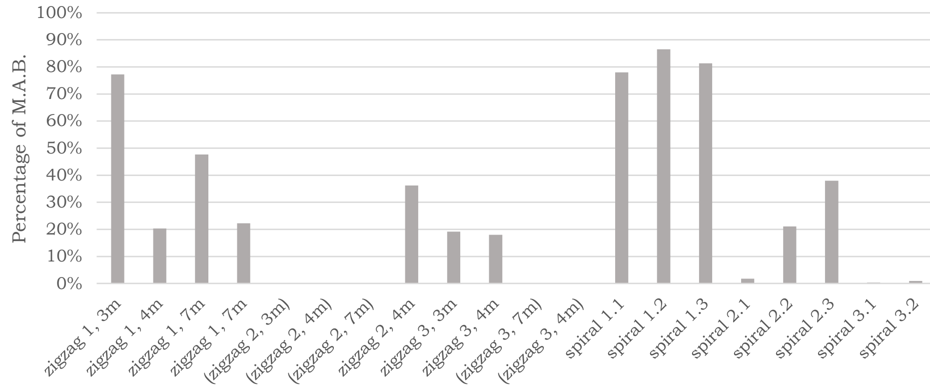


(c) 15^{th} June 2018 zigzag

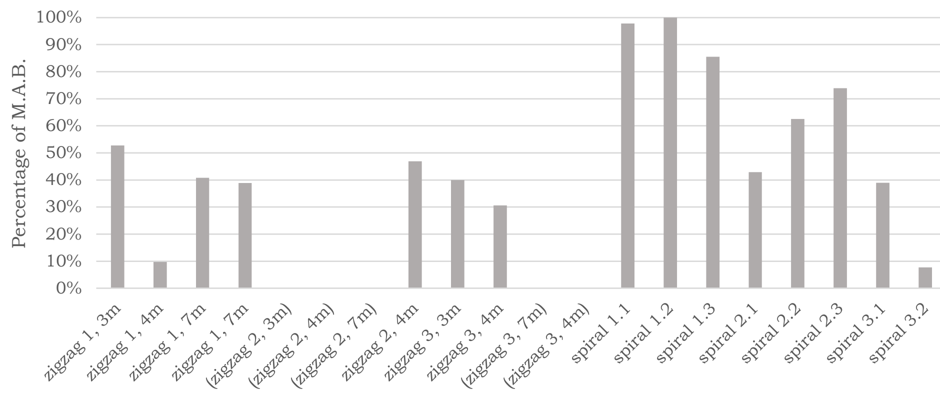


(d) 20^{th} June 2018 zigzag

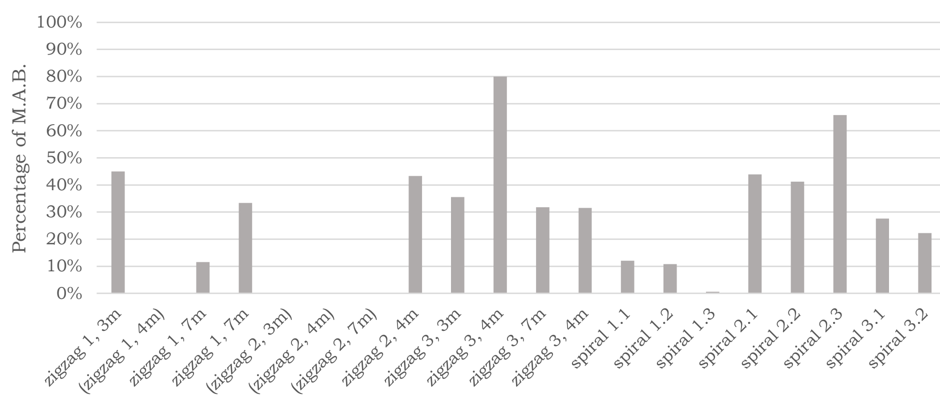
Figure B.1: The percentages of M.A.B measured with the UAV for each flight done for the two flight methods, at the two different days, splitted by height.



(a) 15^{th} June 2018 - Static sensor 1 (3m)

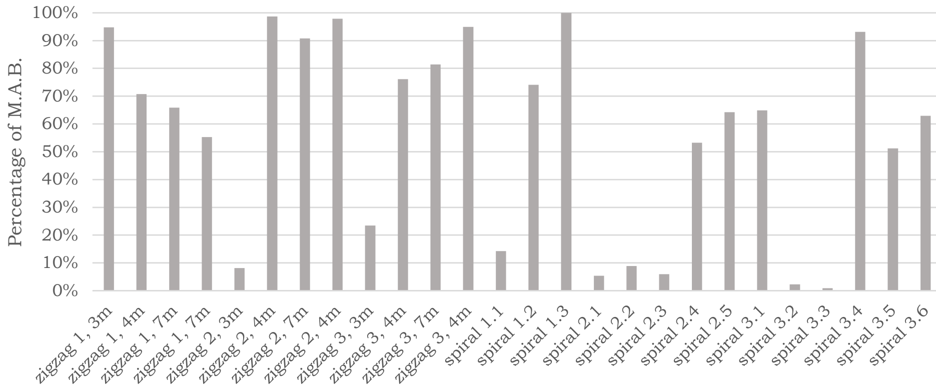


(b) 15^{th} June 2018 - Static sensor 2 (4m)

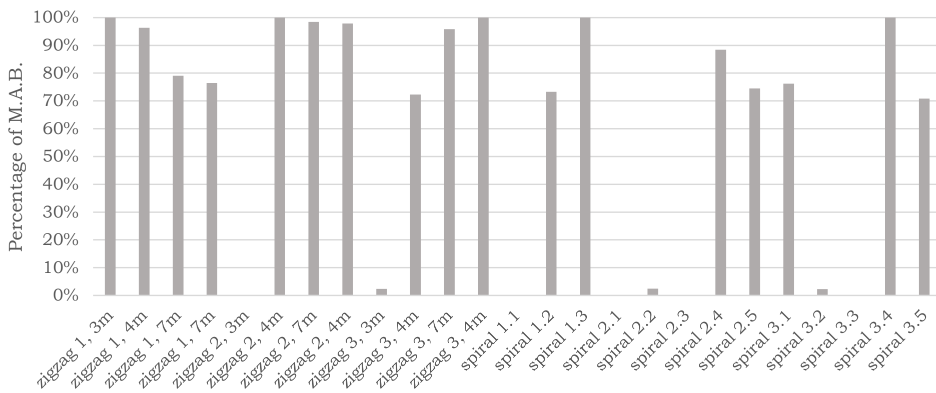


(c) 15^{th} June 2018 - Static sensor 3 (7m)

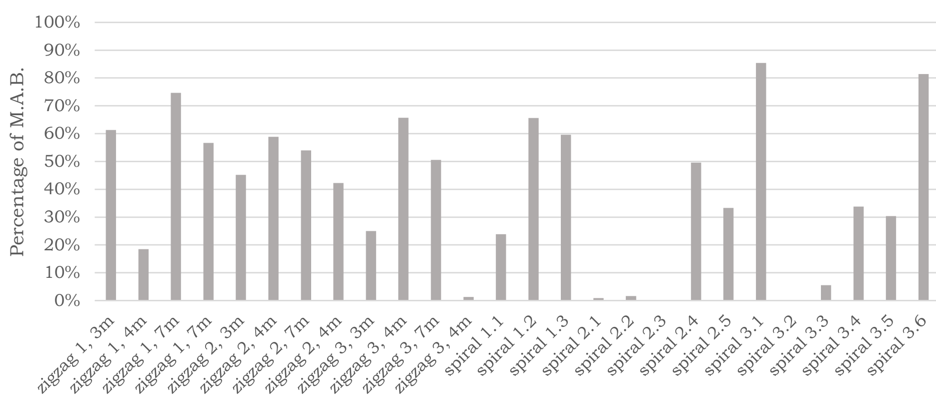
Figure B.2: The percentages of M.A.B measured with the static sensors during each flight done for the two flight methods, at the first day. Axis labels correspond with the UAV flights. Labels between parentheses indicate a missing value due to sensor failure.



(a) 20^{th} June 2018 - Static sensor 1 (3m)



(b) 20^{th} June 2018 - Static sensor 2 (4m)

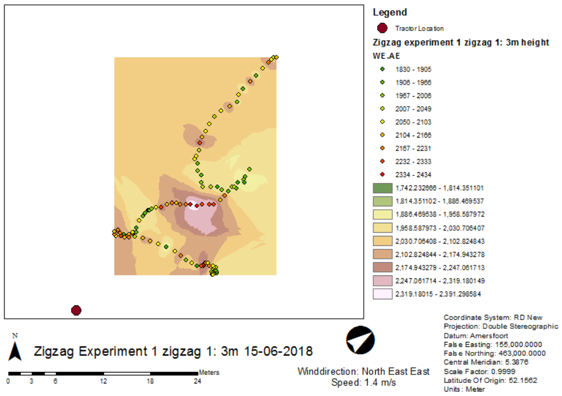


(c) 20^{th} June 2018 - Static sensor 3 (7m)

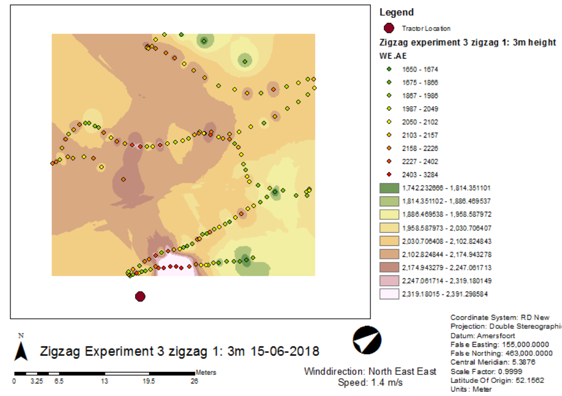
Figure B.3: The percentages of M.A.B measured with the static sensors during each flight done for the two flight methods, at the second day. Axis labels correspond with the UAV flights. Labels between parentheses indicate a missing value due to sensor failure.

Appendix C

IDW Interpolation maps zigzag experiments

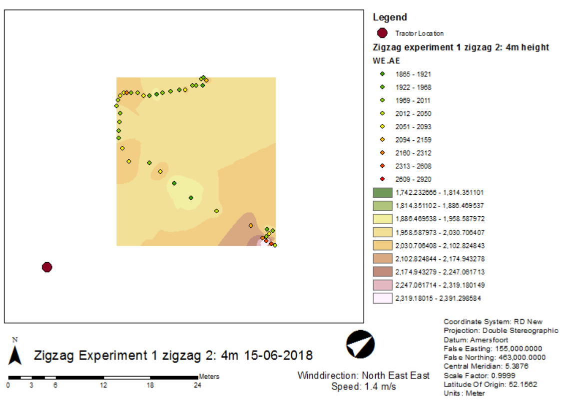


(a)

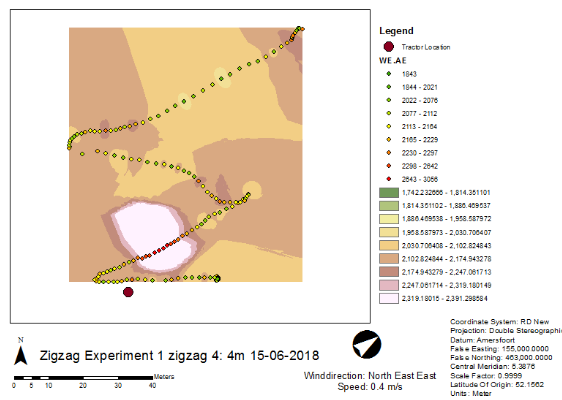


(b)

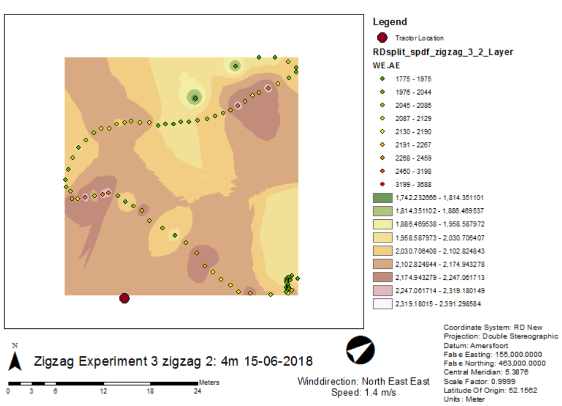
Figure C.1: C.1.a is flown on 15^{th} of June 2018 zigzag experiment 1, zigzag 1 executed on 3m. b is flown on 15^{th} of June 2018 zigzag experiment 3, zigzag 1 executed on 3m.



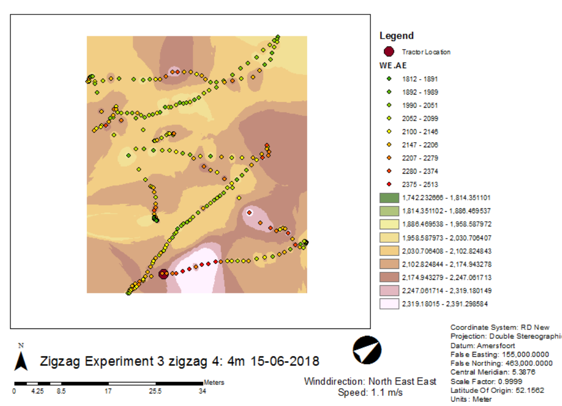
(a)



(b)

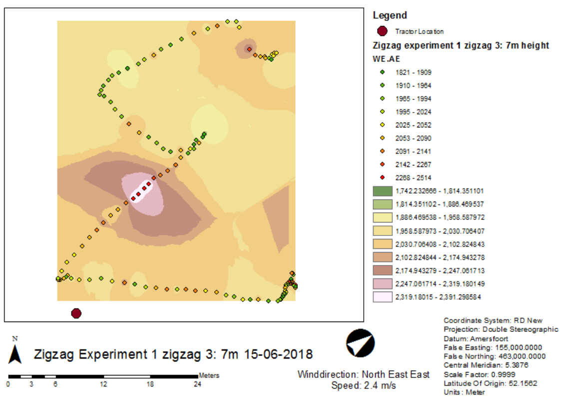


(c)

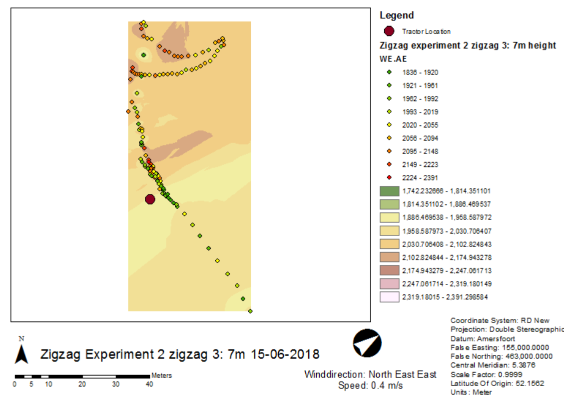


(d)

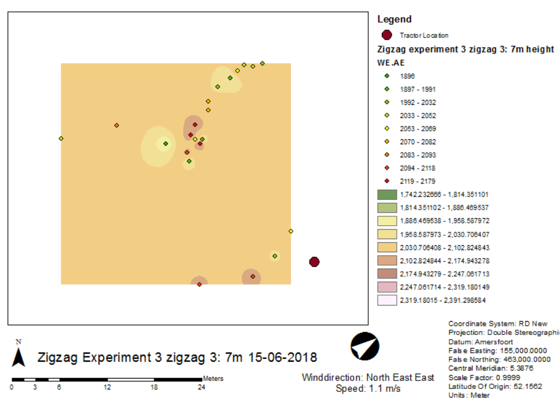
Figure C.2: All the zigzag flight paths and IDW interpolation results flown at 4m on 15^{th} of June 2018 C.2a and C.2b is experiment 1 flight 2 and 4. C.2c and C.2d is experiment 3 flight 2 and 4.



(a)

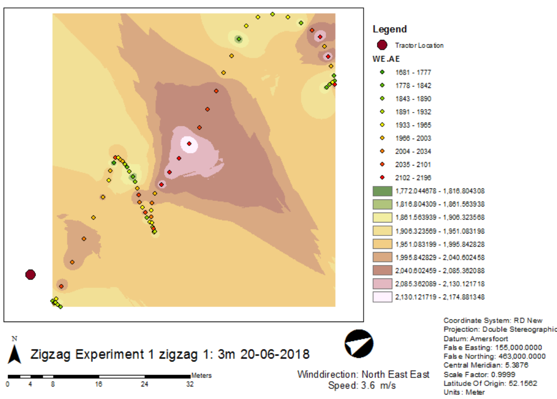


(b)

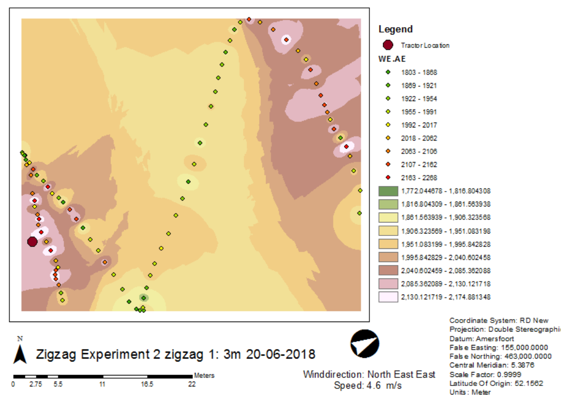


(c)

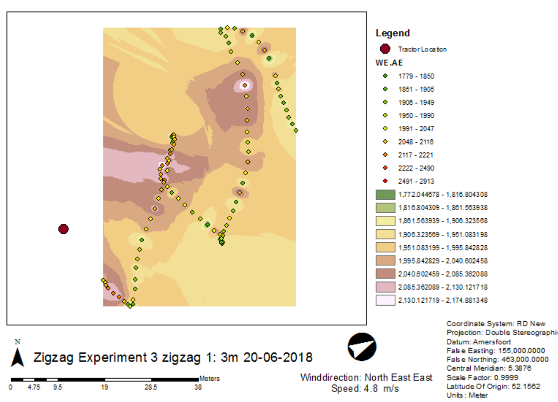
Figure C.3: All the zigzag flight paths and IDW interpolation results flown at 7m on 15^{th} of June 2018 C.3a and is experiment 1 flight 3. C.3b is experiment 2 flight 3. C.3c is experiment 3 flight 3.



(a)

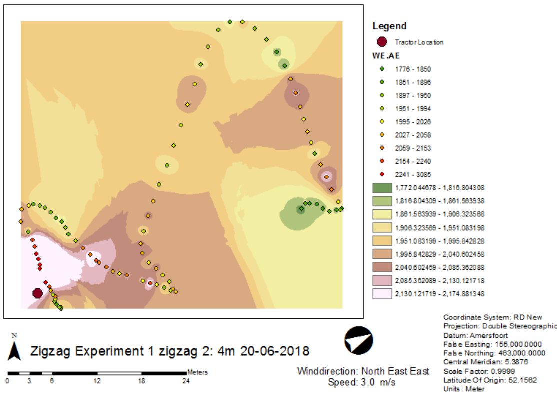


(b)

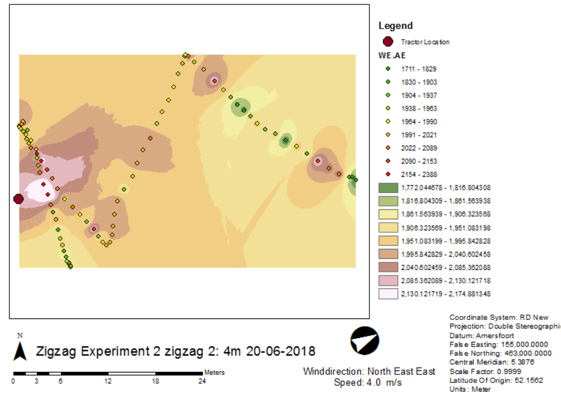


(c)

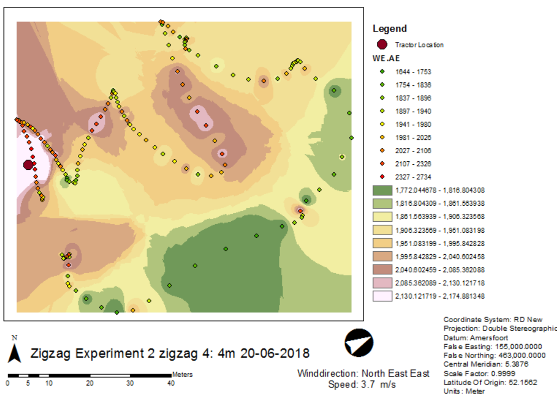
Figure C.4: All the zigzag flight paths and IDW interpolation results flown at 3m on 20th of June 2018 C.4a and is flight 1 zigzag 1. C.4b is flight 2 zigzag 1. C.4c is flight 3 zigzag 1.



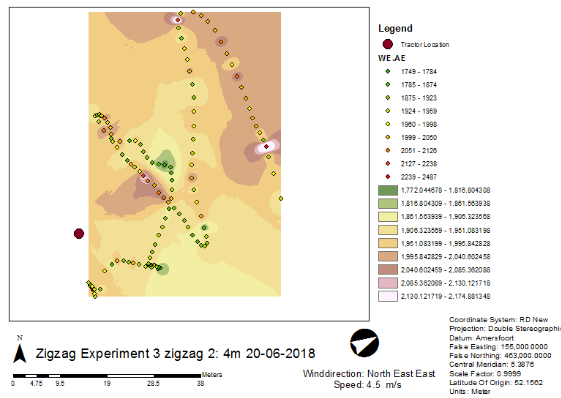
(a)



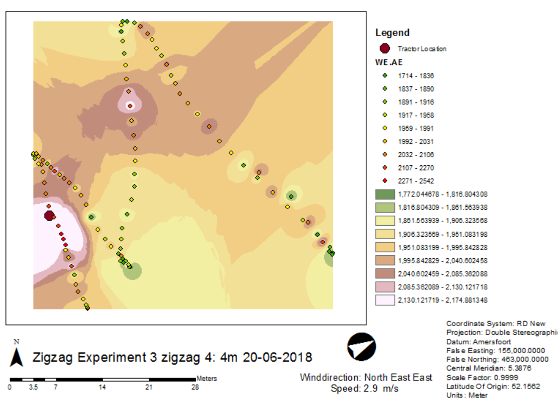
(b)



(c)

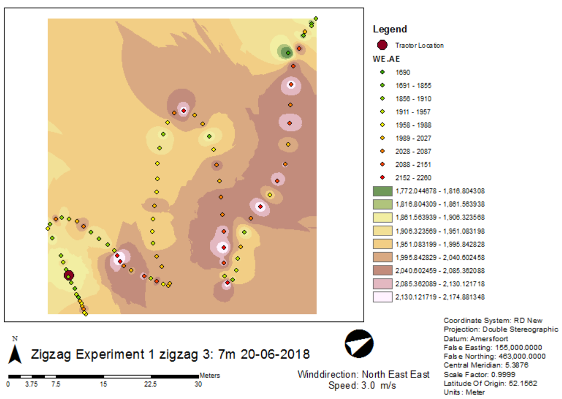


(d)

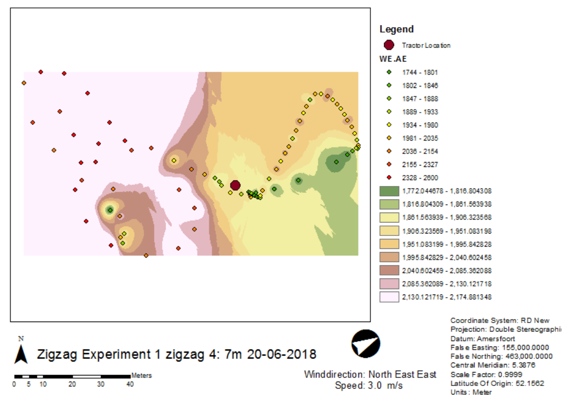


(e)

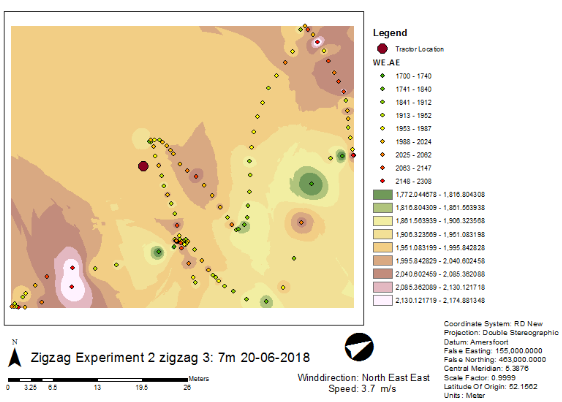
Figure C.5: All the zigzag flight paths and IDW interpolation results flown at 4m on 20^{th} of June 2018 C.5a and is flight 1 zigzag 1. C.5b is flight 2 zigzag 1. C.5c is flight 3 zigzag 1. C.5d is flight 3 zigzag 1. C.5e is flight 3 zigzag 1.



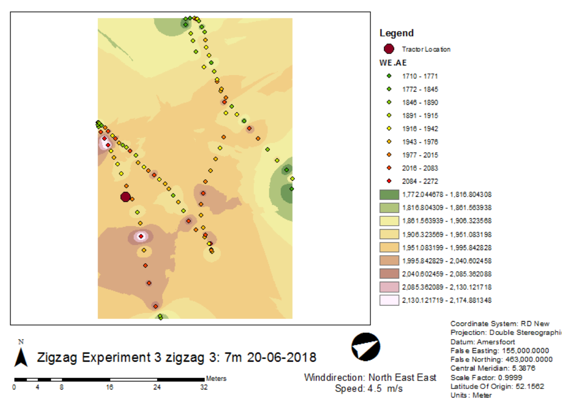
(a)



(b)



(c)

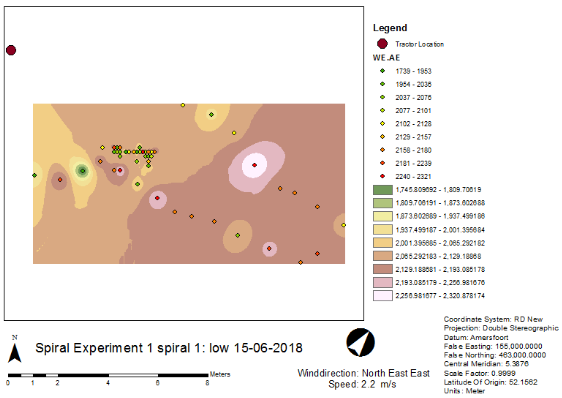


(d)

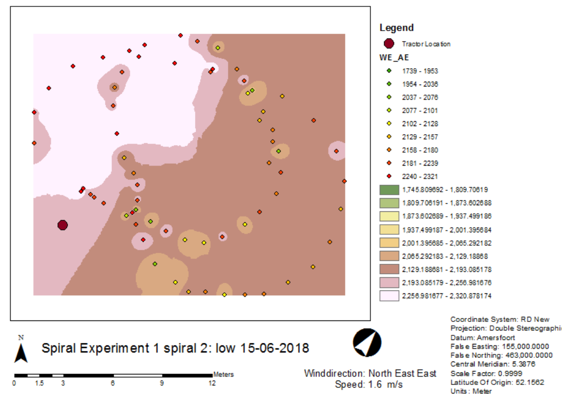
Figure C.6: All the zigzag flight paths and IDW interpolation results flown at 4m on 20th of June 2018 C.6a and is flight 1 zigzag 1. C.6b is flight 2 zigzag 1. C.6c is flight 3 zigzag 1. C.6d is flight 3 zigzag 1.

Appendix D

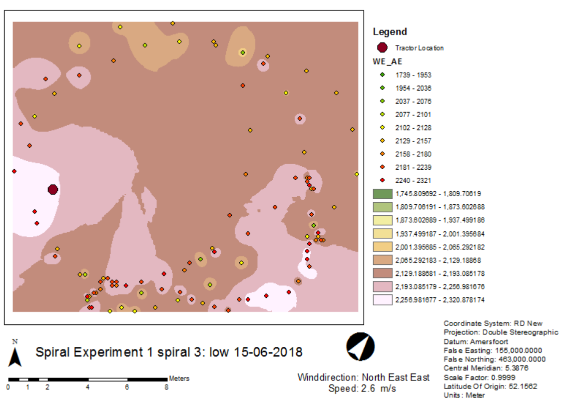
IDW Interpolation maps spiral experiments



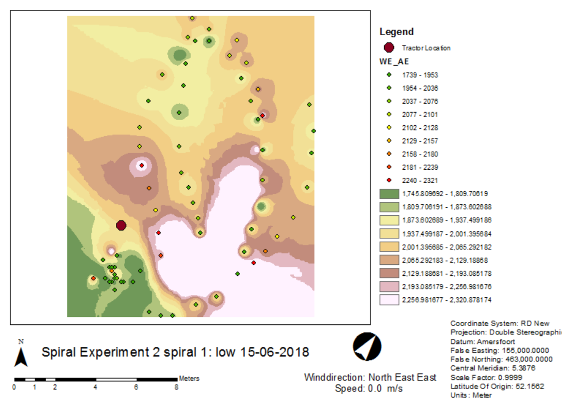
(a) spiral 1.1 low



(b) spiral 1.2 low

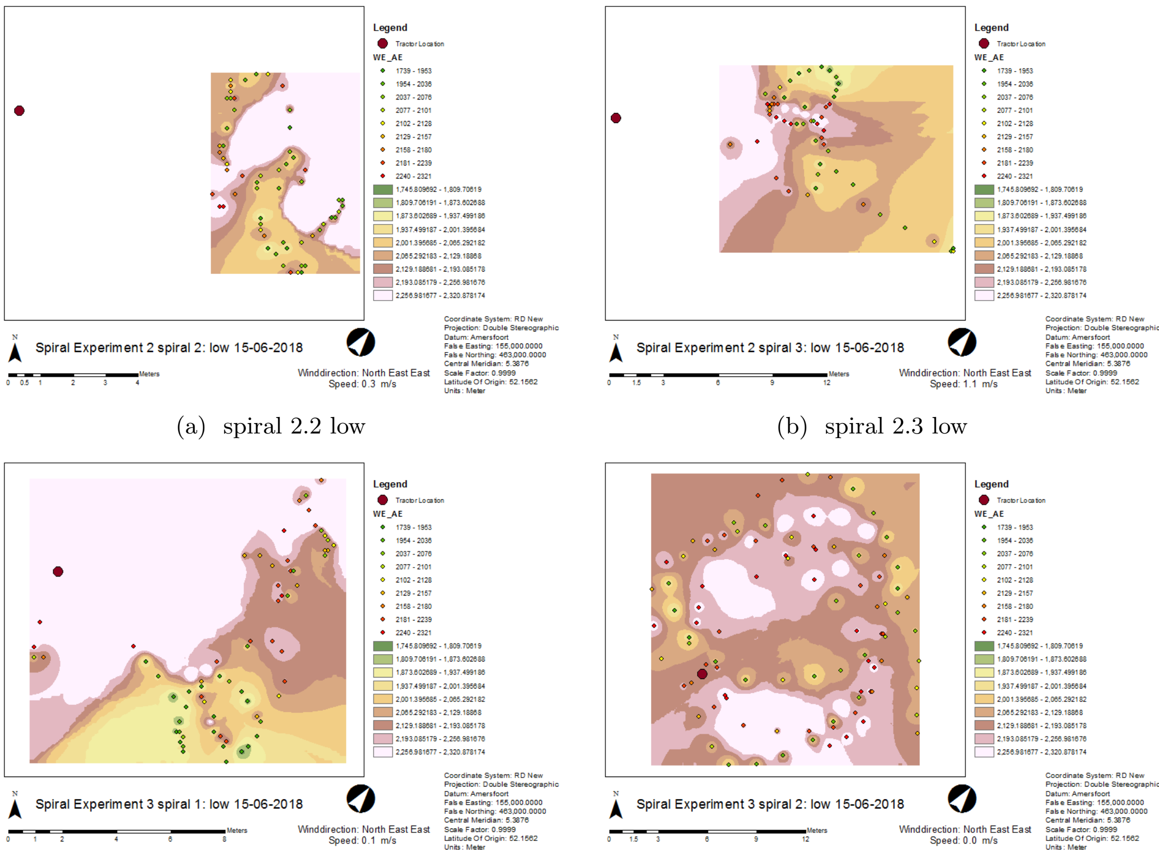


(c) spiral 1.3 low



(d) spiral 2.1 low

Figure D.1: D.1 is flown on 15^{th} of June 2018 spiral experiment 1 to 3, all the lowest parts of the spirals. The height is between 3m to 5m. The experiment is executed 3 times. Within each experiment the spiral is flow 2 to 3 times.



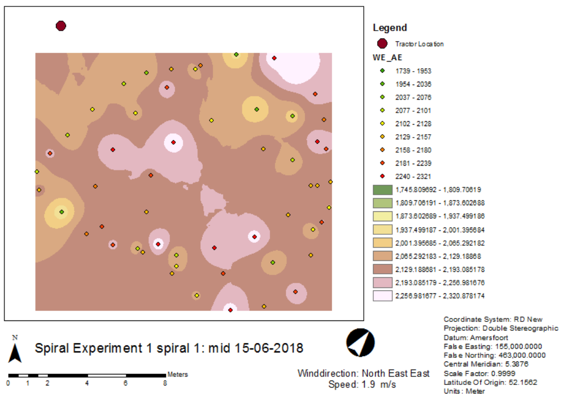
(a) spiral 2.2 low

(b) spiral 2.3 low

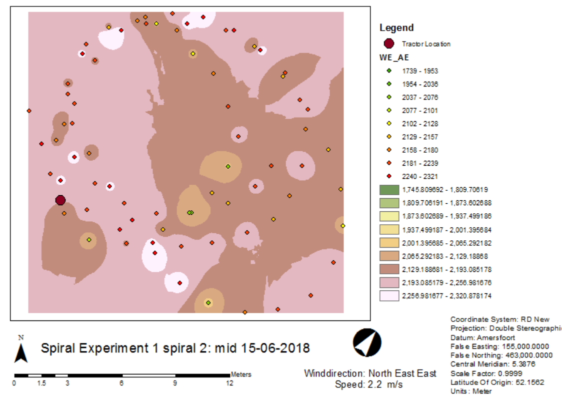
(c) spiral 3.1 low

(d) spiral 3.2 low

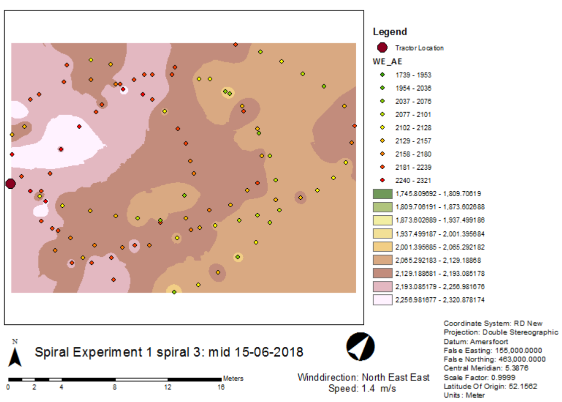
Figure D.2: D.2 is flown on 15^{th} of June 2018 spiral experiment 1 to 3, all the lowest parts of the spirals. The height is between 3m to 5m. The experiment is executed 3 times. Within each experiment the spiral is flow 2 to 3 times.



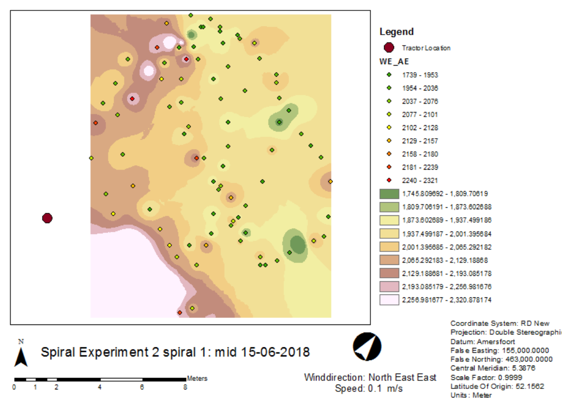
(a) spiral 1.1 mid



(b) spiral 1.2 mid

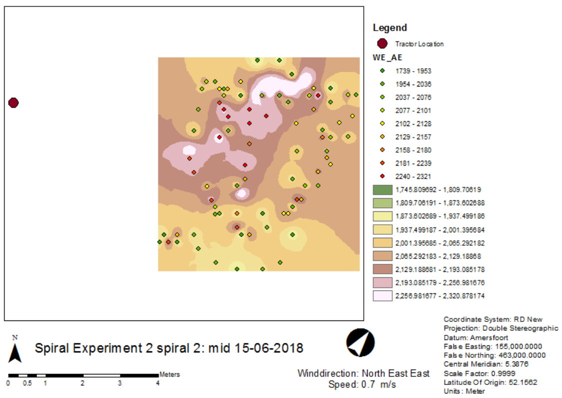


(c) spiral 1.3 mid

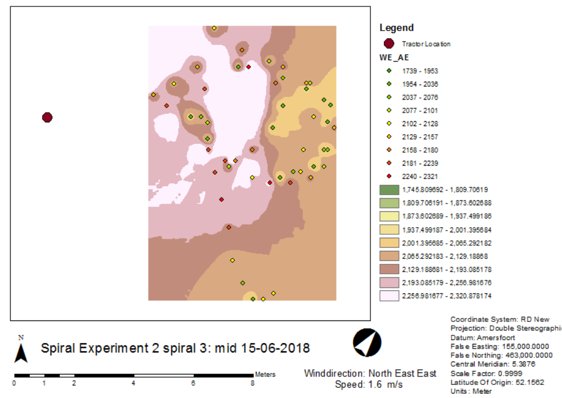


(d) spiral 2.1 mid

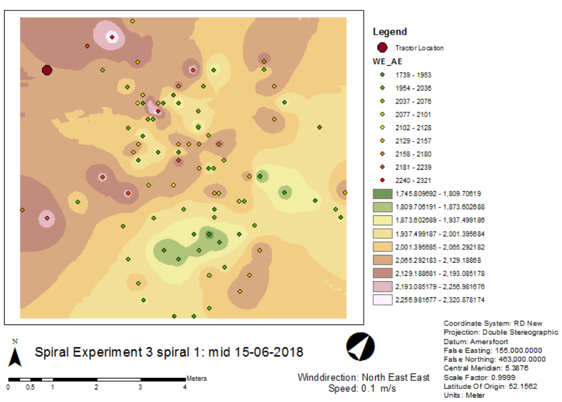
Figure D.3: D.3 is flown on 15^{th} of June 2018 spiral experiment 1 to 3, all the lowest parts of the spirals. The height is between 5m to 7m. The experiment is executed 3 times. Within each experiment the spiral is flow 2 to 3 times.



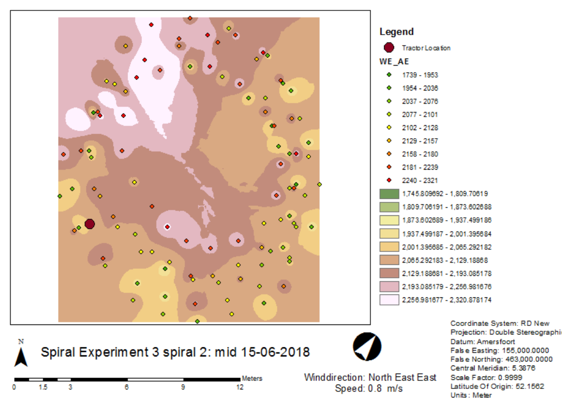
(a) spiral 2.2 mid



(b) spiral 2.3 mid

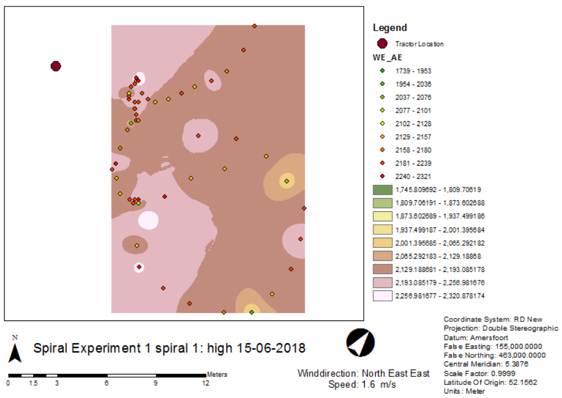


(c) spiral 3.1 mid

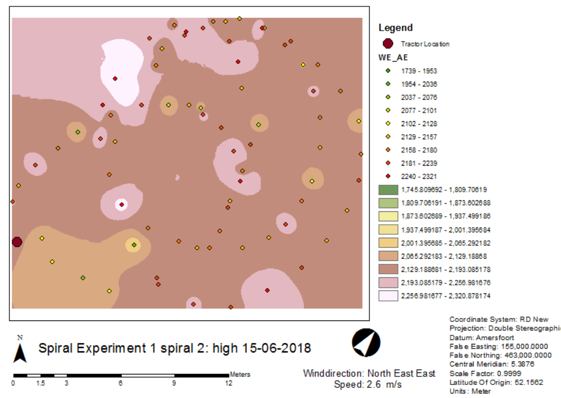


(d) spiral 3.2 mid

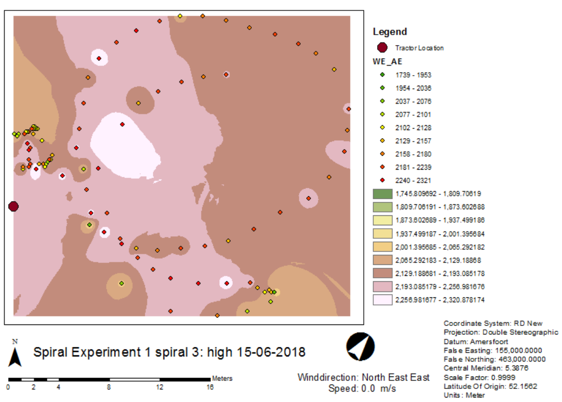
Figure D.4: D.2 is flown on 15^{th} of June 2018 spiral experiment 1 to 3, all the lowest parts of the spirals. The height is between 5m to 7m. The experiment is executed 3 times. Within each experiment the spiral is flow 2 to 3 times.



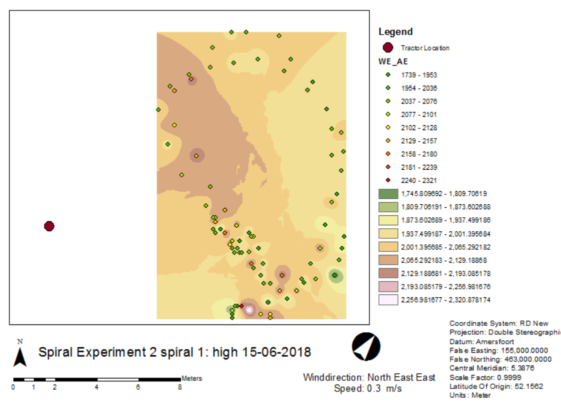
(a) spiral 1.1 high



(b) spiral 1.2 high

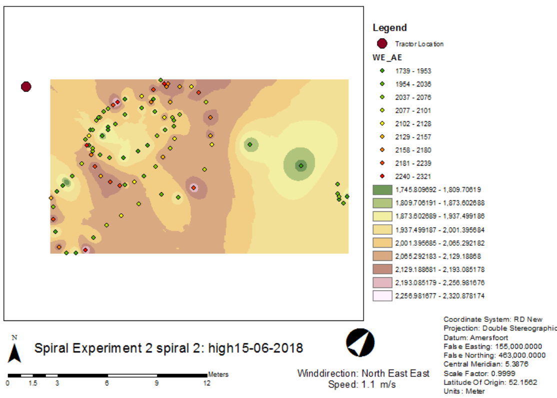


(c) spiral 1.3 high

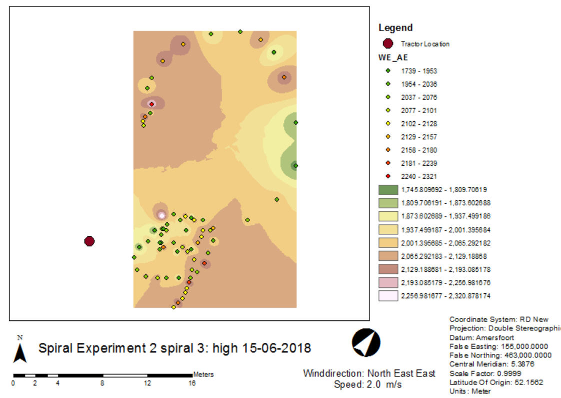


(d) spiral 2.1 high

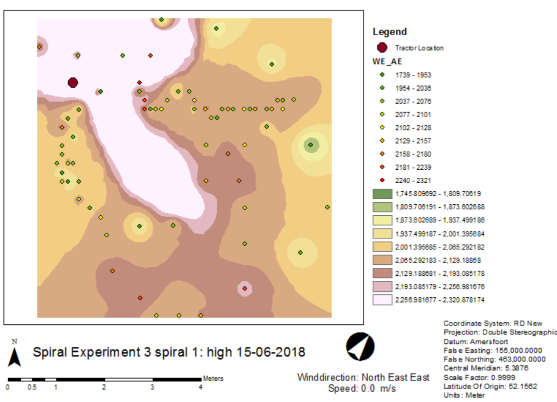
Figure D.5: D.5 is flown on 15^{th} of June 2018 spiral experiment 1 to 3, all the lowest parts of the spirals. The height is between 7m to 10m. The experiment is executed 3 times. Within each experiment the spiral is flow 2 to 3 times.



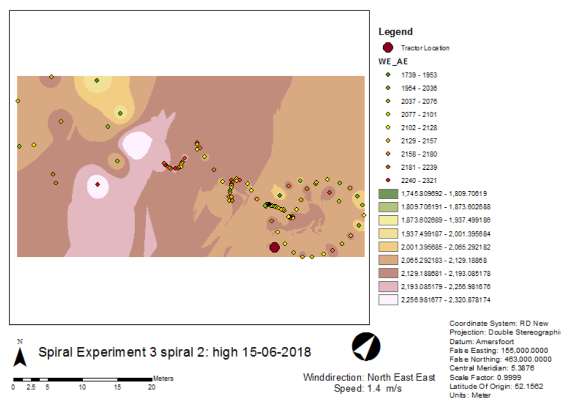
(a) spiral 2.2 high



(b) spiral 2.3 high

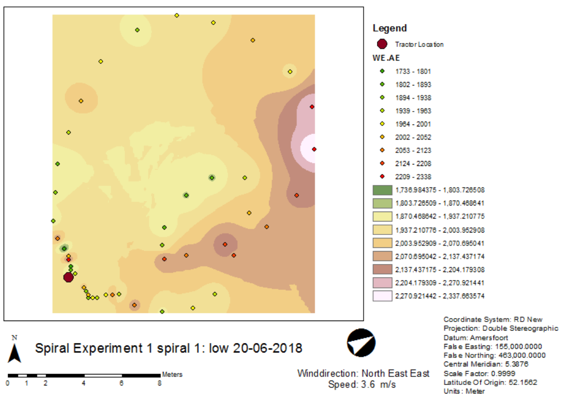


(c) spiral 3.1 high

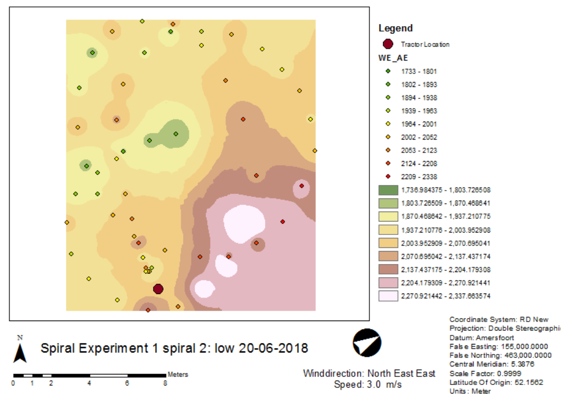


(d) spiral 3.2 high

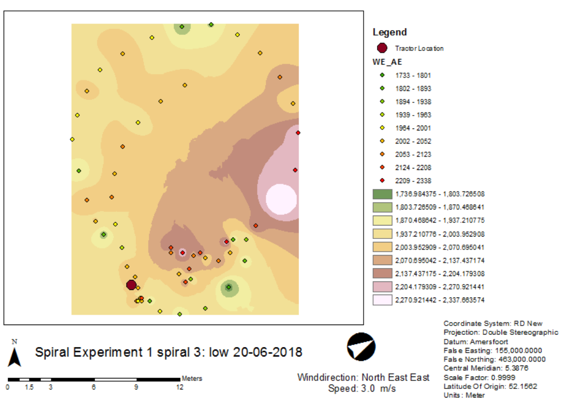
Figure D.6: D.6 is flown on 15^{th} of June 2018 spiral experiment 1 to 3, all the lowest parts of the spirals. The height is between 7m to 10m. The experiment is executed 3 times. Within each experiment the spiral is flow 2 to 3 times.



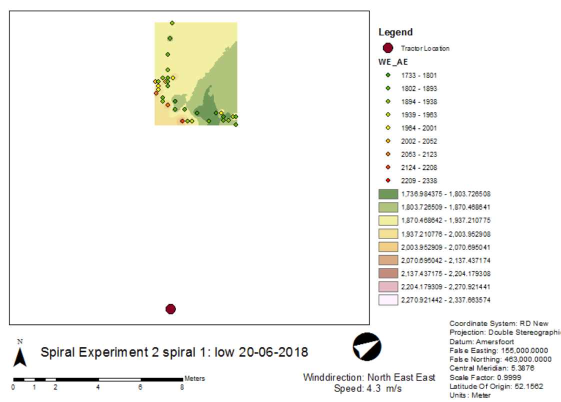
(a) spiral 1.1 low



(b) spiral 1.2 low

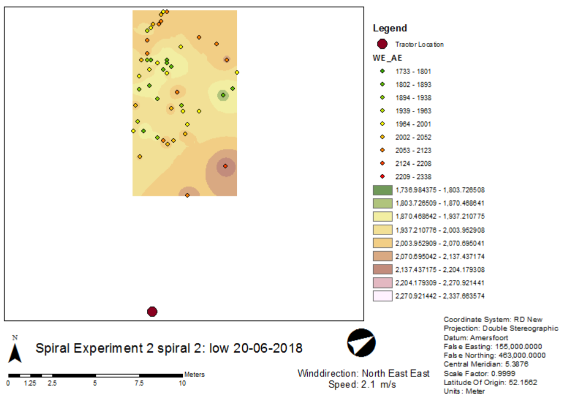


(c) spiral 1.3 low

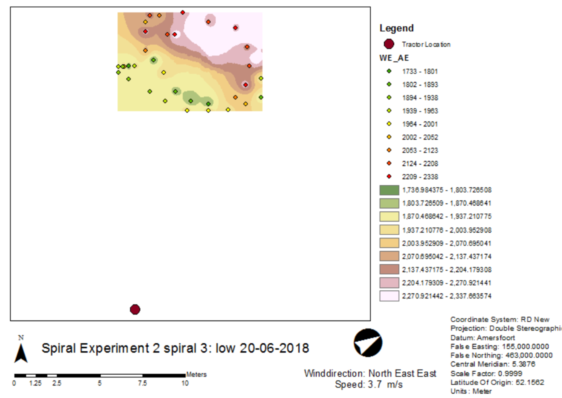


(d) spiral 2.1 low

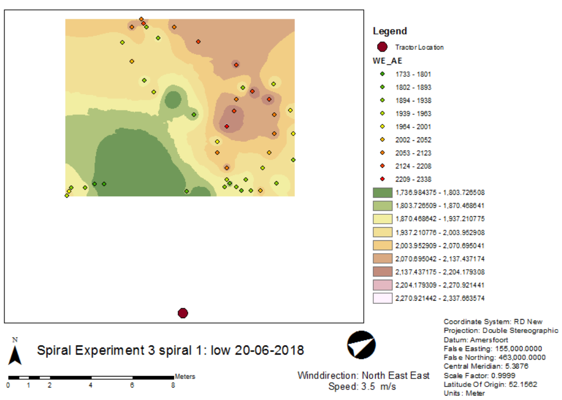
Figure D.7: D.7 is flown on 20^{th} of June 2018 spiral experiment 1 to 3, all the lowest parts of the spirals. The height is between 3m to 5m. Within each experiment the spiral is flow 3 times in experiment 1, 5 times in experiment 2 and 6 times in experiment 3. Only spiral 1 to 3 is shown here, because the extra spirals were not showing new results.



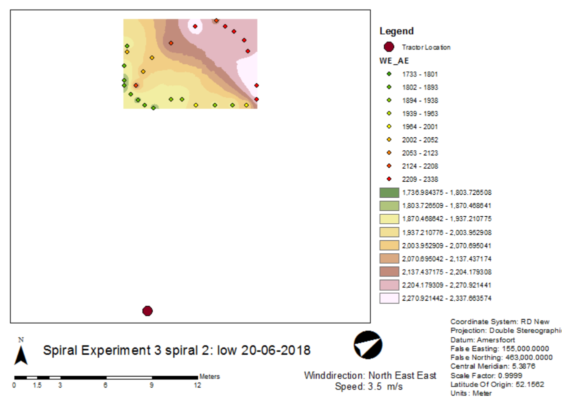
(a) spiral 2.2 low



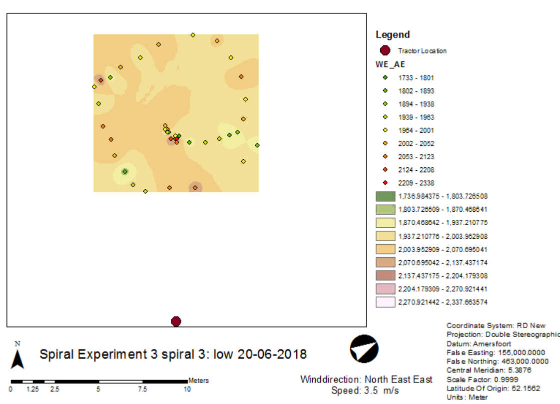
(b) spiral 2.3 low



(c) spiral 3.1 low

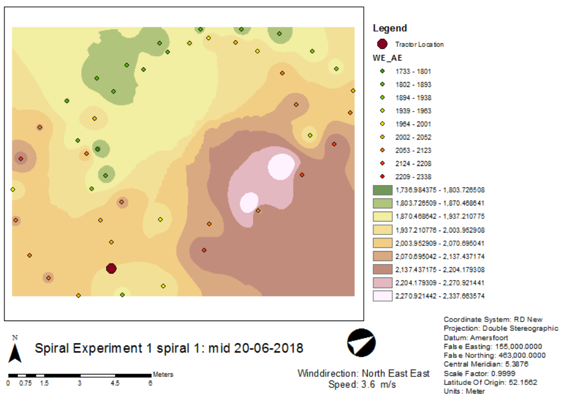


(d) spiral 3.2 low

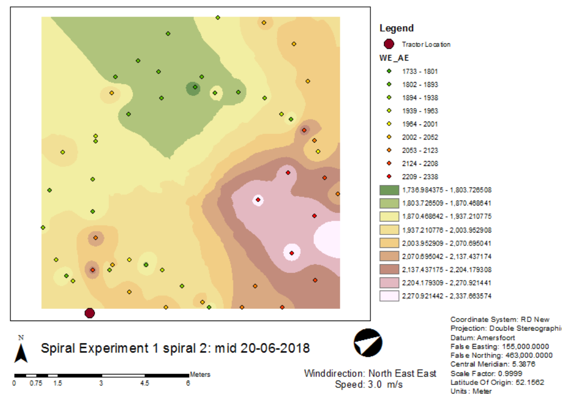


(e) spiral 3.3 low

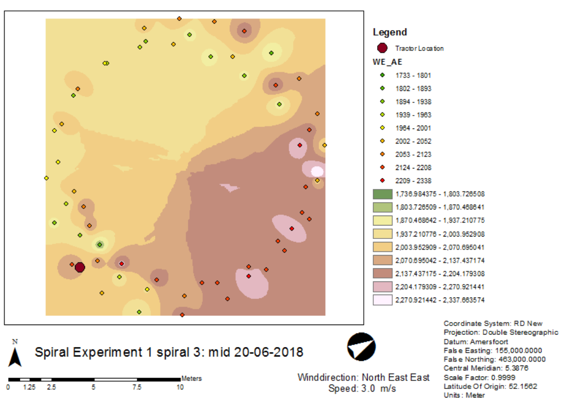
Figure D.8: D.2 is flown on 20^{th} of June 2018 spiral experiment 1 to 3, all the lowest parts of the spirals. The height is between 3m to 5m. Within each experiment the spiral is flow 3 times in experiment 1, 5 times in experiment 2 and 6 times in experiment 3. Only spiral 1 to 3 is shown here, because the extra spirals were not showing new results.



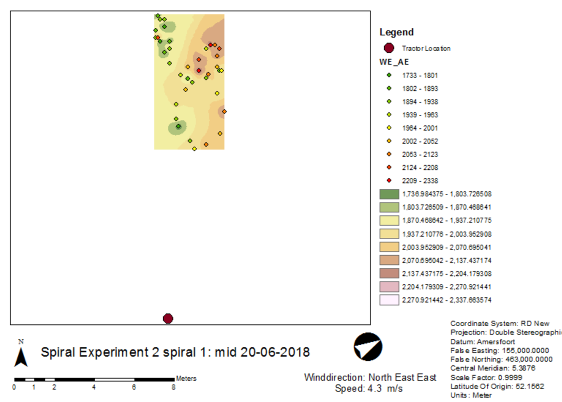
(a) spiral 1.1 mid



(b) spiral 1.2 mid

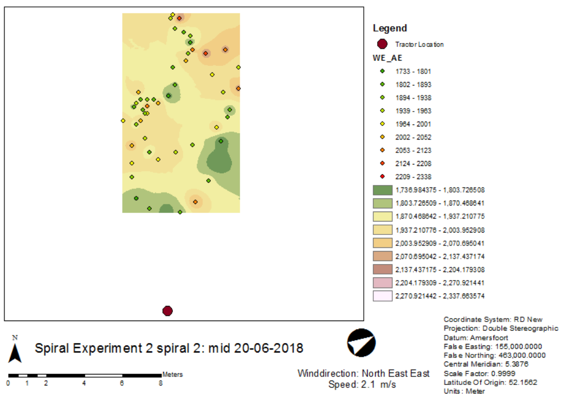


(c) spiral 1.3 mid

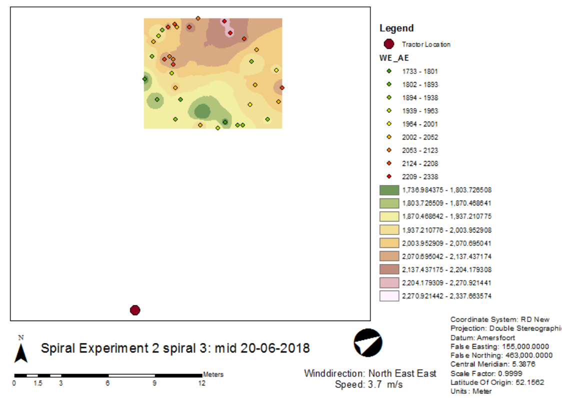


(d) spiral 2.1 mid

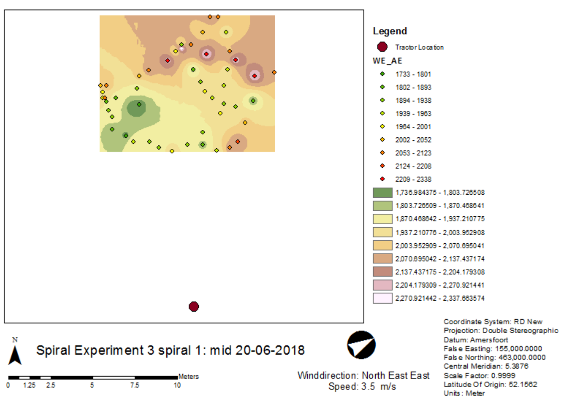
Figure D.9: D.9 is flown on 20^{th} of June 2018 spiral experiment 1 to 3, all the lowest parts of the spirals. The height is between 5m to 7m. Within each experiment the spiral is flow 3 times in experiment 1, 5 times in experiment 2 and 6 times in experiment 3. Only spiral 1 to 3 is shown here, because the extra spirals were not showing new results.



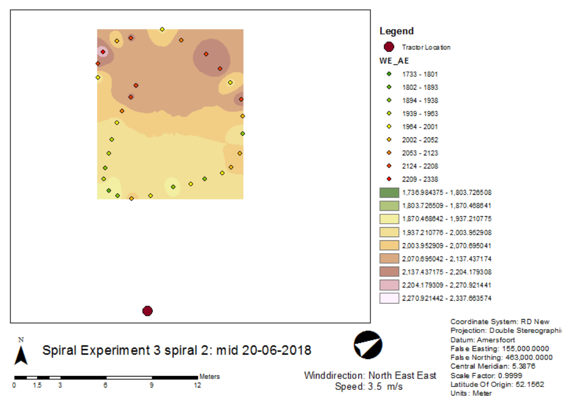
(a) spiral 2.2 mid



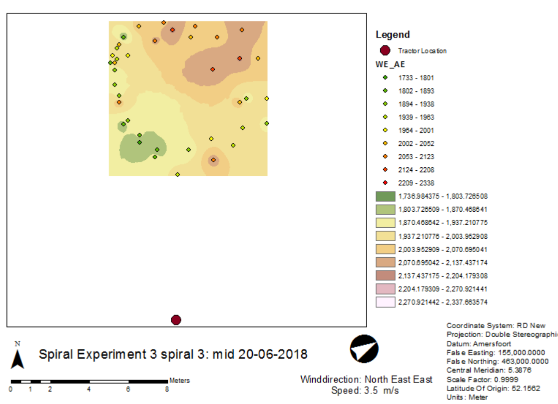
(b) spiral 2.3 mid



(c) spiral 3.1 mid

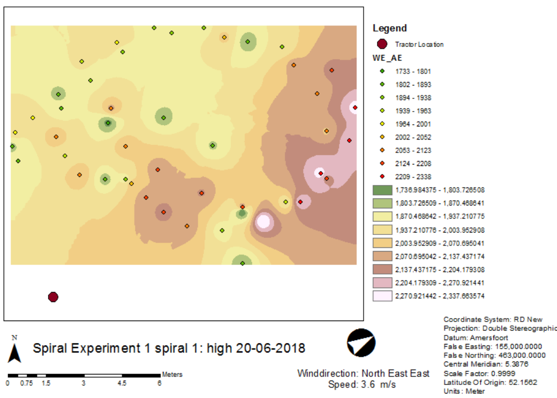


(d) spiral 3.2 mid

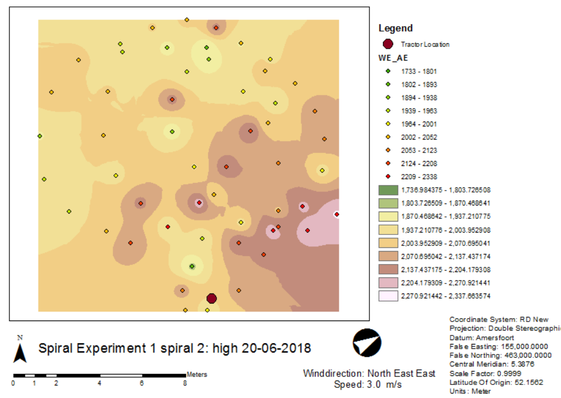


(e) spiral 3.3 mid

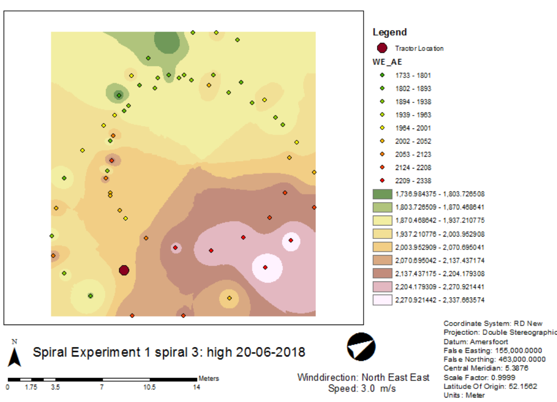
Figure D.10: D.4 is flown on 20^{th} of June 2018 spiral experiment 1 to 3, all the lowest parts of the spirals. The height is between 5m to 7m. The experiment is executed 3 times. Within each experiment the spiral is flow 3 times in experiment 1, 5 times in experiment 2 and 6 times in experiment 3. Only spiral 1 to 3 is shown here, because the extra spirals were not showing new results.



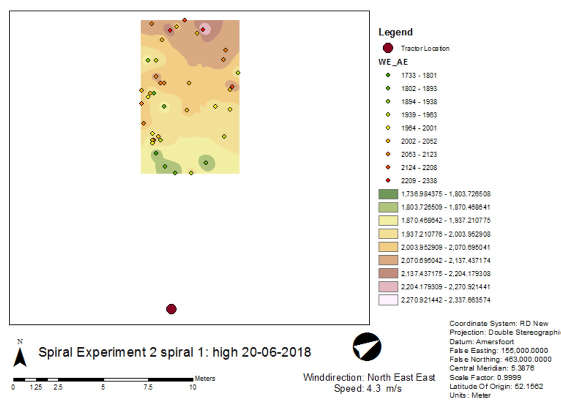
(a) spiral 1.1 high



(b) spiral 1.2 high

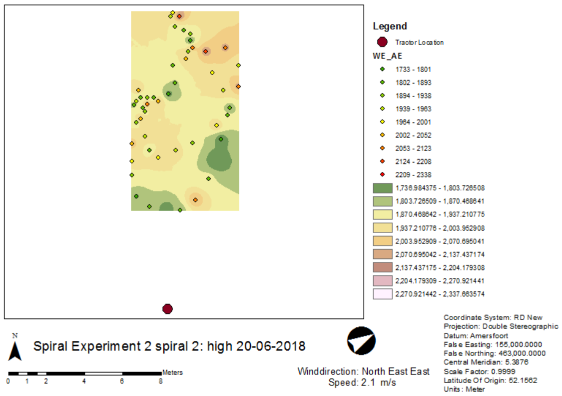


(c) spiral 1.3 high

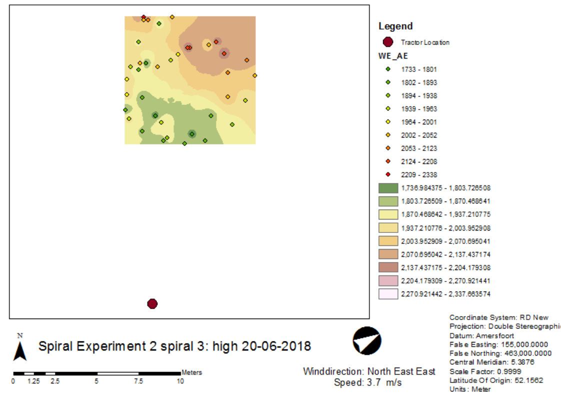


(d) spiral 2.1 high

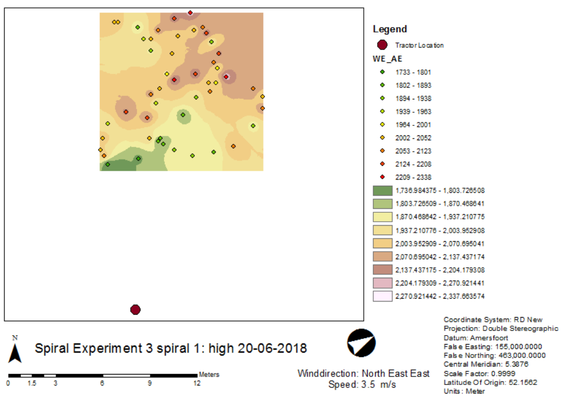
Figure D.11: D.11 is flown on 20th of June 2018 spiral experiment 1 to 3, all the lowest parts of the spirals. The height is between 7m to 10m. Within each experiment the spiral is flow 3 times in experiment 1, 5 times in experiment 2 and 6 times in experiment 3. Only spiral 1 to 3 is shown here, because the extra spirals were not showing new results.



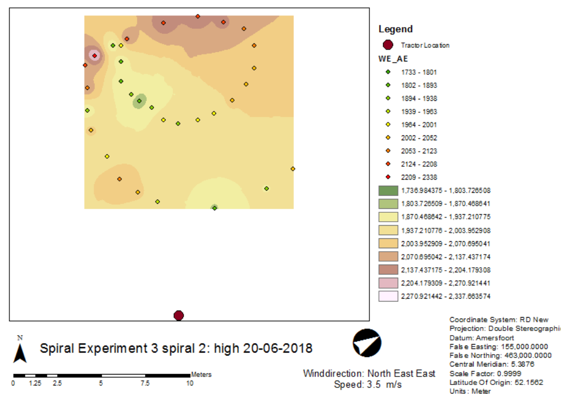
(a) spiral 2.2 high



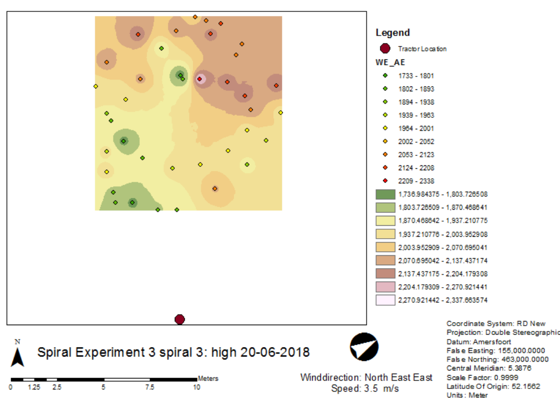
(b) spiral 2.3 high



(c) spiral 3.1 high



(d) spiral 3.2 high



(e) spiral 3.3 high

Figure D.12: D.6 is flown on 20^{th} of June 2018 spiral experiment 1 to 3, all the lowest parts of the spirals. The height is between 5m to 7m. The experiment is executed 3 times. Within each experiment the spiral is flow 3 times in experiment 1, 5 times in experiment 2 and 6 times in experiment 3. Only spiral 1 to 3 is shown here, because the extra spirals were not showing new results.