Airborne Sampling-Sensing of Distal Volcanic Ash

2016 FINAL YEAR PROJECT PROGRESS REPORT

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0.0 ABSTRACT

Volcanic ash can be very harmful to aircraft and the structures that are built up and rely on them. The project was given to a University of Canterbury final year project team with five members. IR satellite imagery gives a good 2D map of the volcanic ash cloud but does not give depth mapping. Having a depth model to the cloud will give the ability to tell planes what altitude zones are safe to fly in. This can save a vast amount of fuel and time rather than flying around the cloud, which sometimes isn't possible and cancels flights. A weather balloon filled with helium will take an unman aerial vehicle up to 40,000 feet and release it, while sensing for volcanic ash on the way up and down. My assignments for this project are to design and develop an ash sampling unit and pre-sensor chamber. The sample will need to land on a membrane that a scanning electron microscope can easily view. The most likely membrane will be carbon tape in which the volcanic ash can embed its self on. Testing of the carbon tape will need to be done in a closed loop test chamber where the density of volcanic ash is constant. This chamber is yet to be built. The sensor we will be using (providing it performs well) is the OPC-N2 which draws in air and can't have air forced in to it, so providing it with a chamber to slow air down is critical to its operation.

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1.0 PROJECT OVERVIEW

Volcanic eruptions can cause a vast array of hazards to humans including to aircraft in the form of damage to the engine and delayed flights. New Zealand's (NZ) Defence Technology Agency (DTA) has seen this problem as being a large risk to NZ because its primary form of international travel is through the use of aircraft. NZ is situated on the Ring of Fire, which is a band of area that stretches from Oceania up to the Artic passing through Asia then down to Chile past the Americas and equates for 75% of the worlds volcanos. With NZ being in this volcanically dense area with surrounding countries having volcanos also compounds the risk of volcanic activity air space. The DTA also have the agenda to determine how long an aircraft can fly for in a volcanic ash (VA) cloud, for military and search and rescue events in wake of an eruption. Current methods for detecting VA are by using IR satellite imagery to track the movement of the VA cloud. This how every doesn't give data on what height the VA cloud is at, so is only good for avoiding the VA cloud by flying around it.

Events that effect air travel are evident in Australasia with an eruption of Mount Sangeang in Indonesia on May 31st 2014 [1] which disrupted flights as far away as Brisbane. On Jun 13th, 2011 a Chilean VA cloud [2] drifted across the Pacific Ocean to NZ and several local aircraft companies canceled flights or flew at low altitudes. So it is evident that NZ is affected by VA.

Figure 1. Mount Sangeang in Indonesia volcanic eruption [1]

The current standard for flyable atmospheric conditions allows for $4 \times 10^{-6}\ kg\ m^{-3}$[3] or less. This doesn't account for the size of particle and its effects on engines. Figure 2 shows how the larger particles of VA clouds drop off closer to the volcano with the smaller particles traveling a much greater distance. Because of the lack of data and experimentation of how particle size effects engines I could conjecture that smaller particles past through an engine with little or without damage.

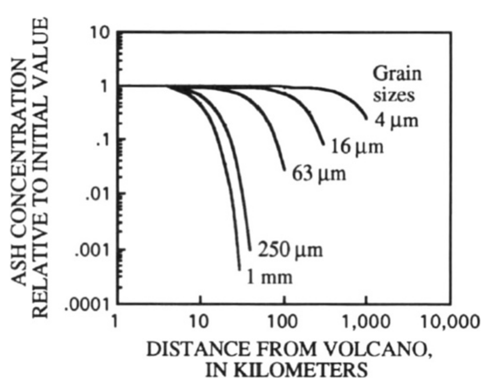

Figure 2: Dispersal of VA from volcano [4]

A low cost solution to this problem is needed with current VA testing aircraft costing in the millions. Testing would have to take place up to 40,000 feet, the maximum altitude of current passenger aircraft and will need to have several functions, including sensing the present of VA, density of VA, VA particle size, taking a physical sample and standard plane sensors such as GPS, compass, air speed and barometer. Data would have to be transmitted to ground station real time in case the test could not be recovered.

The team has decided to us a weather balloon with an unmanned aerial vehicle (UAV) deployed at 40,000 feet. The UAV is likely to be a glider that is unpowered. This is low cost because a powered UAV flying to 40,000 would require a large airframe which our budget would not cover. Before we purchase the air frame we need to know the size and mass the of the payload. Getting the sensors to detect the VA has been the first priority. The team has ordered an expensive sensor that can give density and particle size for between 0.38 to 17 μm [5] and some cheaper sensors that count particles. Following the arrival of the sensors they will be tested in a controlled chamber using real VA. The expensive sensor, OPC-N2, can't have air forced into it, as it has its own fan to draw air in. A chamber prior to the OPC-N2 is needed to make sure the air is still before activating the OPC-N2. To get a physical sample of VA on the UAV will be difficult because no off the shelf products are available so a custom unit will be needed to be designed. Both the chamber before the OPC-N2 and the sampling unit will be my focus for the project. This will include testing of the units in some form such as a closed loop wind tunnel with VA present.

The airframe will be picked after the sensors have been finalized, but the telemetry, autopilot and battery can all be purchased and tested prior. The team also has the use of the airframe and autopilot from the NIWA project in 2015. This airframe is likely to be too small for our use because the payload volume is too small, but we can use this airframe for testing of the telemetry and autopilot.

Individual parts

Jamie
- Testing of sensors, designing test chamber

Jake
- Modelling of various systems

Mike
- Telemetry and autopilot systems

Parth
- Electrostatic sensor

Ryan
- Sampling of VA and pre-sensor chamber

2.0 PROGRESS TO DATE

2.1 Group Progress

The initial decision we had to make was how to get the sensor pay load up to 40,000 feet. The idea to use a weather balloon filled with helium was from the DTA and suggested providing the budget. A balloon gives cheap lift up to the set altitude then a UAV attached with the payload can fly back to a specific ground point. Because weather balloon is free to move with the wind, there is a possibility that the balloon is taken far off course and is too far to away for the UAV to fly back. To make sure this doesn't happen prior to launch weather forecasts need to dictate where the balloon is released from.

The project has been broken down into two stages. First designing the sensors, electronics and telemetry, secondly getting the air frame. The two main reason for this was because the time to build and put all the systems working together will take longer than finding an air frame and once the payload has been finalized we can find an air frame to fit that volume. The DTA also specified to buy off the shelf products so the team didn't need to spend the whole project just developing sensors.

Sampling on the way up and on the way down is a possibility. The UAV will approximately traveling at $5\ ms^{-1}$ on the way up. The characteristics of the VA flowing inside the UAV will change because gravity will be operating in a different direction. This may be an advantage or a disadvantage.

The sensor we have brought but not tested is the OPC-N2 and costs $500, this gives us the two readings we want, particle density in air and particle size. The sensor has a small form factor, 75x63x60 (mm). Getting to this point of finding a sensor that gives us the readings we need has been a long process. This is yet to be tested. The OPC-N2 uses a fan to draw air in, and measures the light scattered from individual particles. The OPC-N2 should not be used when there is no air to draw in or when air is forced into it, it should draw air in that is static. This will be one of two jobs I am to complete. Making sure that when the OPC-N2 is operated there is air for it draw in and no air rushing in to it.

To control the UAV while it is out of line of sight a Pixhawk will be used. This unit gives autopilot functionality for a vast array of UAVs. This is a very commonly used autopilot system that University use and NIWA project form last year used. The Pixhawk outputs to several different devices such as, servos, telemetry and a buzzer and inputs consist of air speed, GPS, compass and battery readings. One thing that is unknown is how the autopilot works in low density air at 40,000 feet. If upon release from the balloon the UAV becomes unstable and becomes uncontrollable, then when the air gets dense enough will the autopilot regain control. This is too hard to test but a small drag shoot may be able to orientate the UAV in the downward direction, then releasing once the autopilot has control.

A static testing chamber will be made to test the sensors and compare them to each other. This will involve adding VA with a known mass to the chamber with known volume to get a value for the density then compare this value to what the sensors read.

An electrostatic sensor is also under development. Even though the DTA wanted off the shelf parts the simplicity of the sensor makes it a viable option. A conductive probe is placed on the front of the UVA and when partials hit it a charge is transferred to the probe; the voltage is then read. Periodically the probe will be earthed to start the reading again. The VA cloud is charged because it is constantly rubbing on other particles [6]. Currently there are no methods for determining any data from the voltage read other than the UAV is in VA.

One team member did a case study to see whether a camera could pick up the VA but was unsuccessful.

2.2 Personal progress

The two parts of the project I am responsible for are the sample collection unit and the pre-sensor chamber. Because the sensor unit is unknown at this point I have been unable to do any work on the pre-sensor chamber. I have started work on the sample collection unit and doing research into what is needed for a sample.

The mass needed for a sample is small as the density of VA in the air is going to be $2 \times 10^{-6}\ kg\ m^{-3}$ at a minimum and $10 \times 10^{-6}\ kg\ m^{-3}$ at the maximum. For the calculation $4 \times 10^{-6}\ kg\ m^{-3}$ will be used, as it is a figure that is on the minimum bound of the density. Sampling on the way up will give a constant velocity air intake which makes it easier to model and the direction of the airflow is known. The vertical velocity is assumed to be $5\ ms^{-1}$. The mass of a sample was decided to be $0.5 \times 10^{-6}\ kg$ at a minimum. This was based off information given by the DTA and their experience with samples of VA. A minimum of $0.1 \times 10^{-6}\ kg$ was possible but was determined to be not robust enough. If two to three milligrams were available to capture chemical analysis would be achievable, but with the current mass goal this will be difficult to achieve. Because the volume in the airframe is very limited a small sampling unit is needed, the problem with using a small unit is that the period of time sampling becomes very large. Figure 3, shows a calculation of the sample time vs sample diameter (assuming sample area is circular). With five minutes open being far too long and 50mm being quite large (considering multiple samples areas will be needed for multiple samples). My script for this calculation can be found in Appendix 1. One minute or less will be an ample amount of time for the sample to take place. This gives a diameter of $23mm$ or greater.

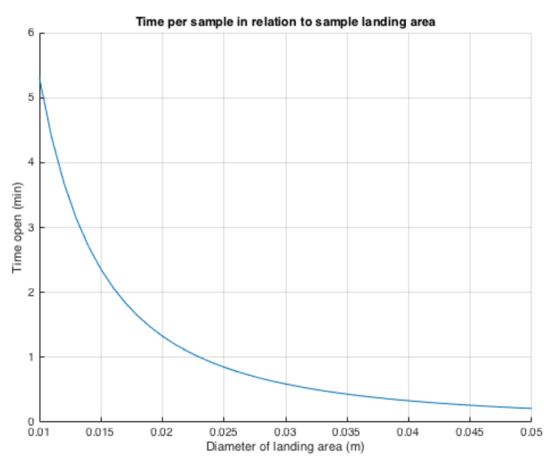

Figure 3: The time the sample will be taken over plotted against the diameter of the contact area

What the VA attaches to on the sample area is also very important because of how the DTA will analyse the sample after capture. The DTA will use a scanning electron microscope to analyse the VA which uses carbon tape to hold samples on. Having the sample land on the carbon tape will be ideal but this may be difficult because it will not let air through, so can only be used for direct contact sampling. The DTA has provided information about how carbon tape doesn't have any trouble holding a sample of VA, but when the UAV is at altitude these properties may change because of the low temperatures. The DTA will be testing a sample of VA on carbon tape in a cold environment in the coming week. Filter paper is another option which will allow air to flow through but this isn't ideal for viewing under the microscope and may be too restrictive to airflow.

My proposition is that an air inlet directs air with VA present directly onto carbon tape that is placed at an angle to the flow. As seen in Figure 4, the direction of the air flows and contracts the tape then flows out to the side. A possibility of pulling a vacuum using the wind rushing past the UAV to help draw air though the system. Testing of this is crucial to see if it will work.

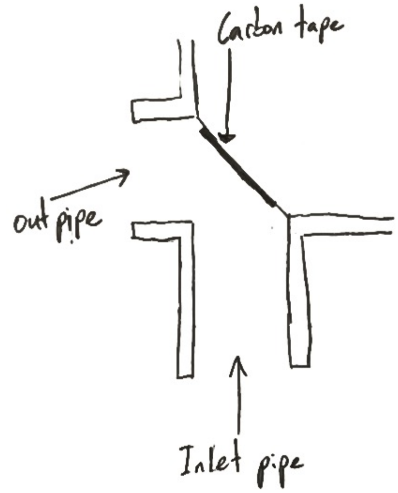

Figure 4: Sketch of idea for carbon tape capture method

To have multiple samples a rotary system would be required where the inlet and outlet tube position is constant with the samples area rotating in and out. Having it rotate would allow easy control with a micro servo. Figure 5 shows a concept with the intake directing air at a surface with carbon tape then ejecting the used air out the side. Figure 6 shows the rotary wheel with a circular contact area diameter of 23mm. Because of the unique shape, the rotary wheel be likely to be 3D printed. VA may have an issue with 3D printed parts as they tend to be porous, so a subsite method of manufacturing may be needed.

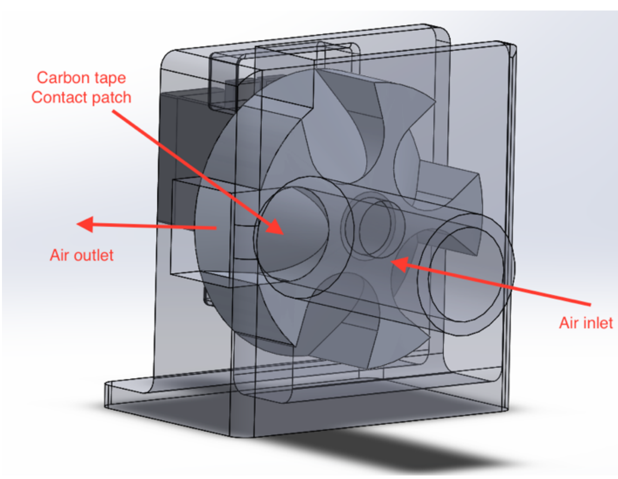

Figure 5: Rotary VA sampling unit concept

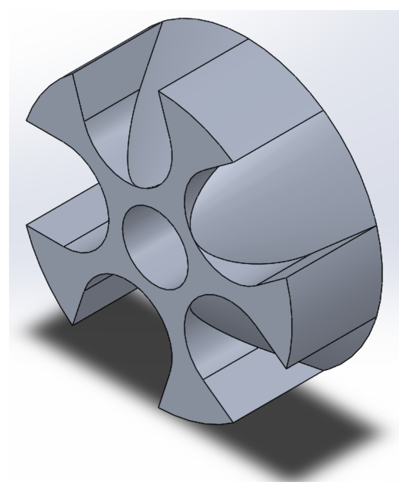
Figure 6: VA sampling unit rotary contact part

3.0 REMAINING TASKS

3.1 Group tasks

As a group there is more to do and is as follows.

- Build VA testing chambers
- Testing OPC-N2
- Telemetry testing
- Pixhawk testing
- Modelling of UAV - battery usage, aero dynamic effects, UAV altitude mapping, GPS waypoint calculating
- Electrostatic sensor design and testing

3.2 Personal tasks

I will be working on testing to get the best sampling membrane. The first test will be to see if carbon tape will get enough VA embed on it. To test this a closed wind tunnel will be needed with the density of VA be controllable, this will be a difficult challenge. To replicate taking a sample on the UAV on the way up traveling at a rate of $5\ ms^{-1}$ would be a reasonable air speed. The team have discussed that a closed loop system will be the best way to keep the density the same, and produced using square air ducting commonly used in building ventilation (See Figure 7). A fan inside the loop will simulate wind and move the VA around.

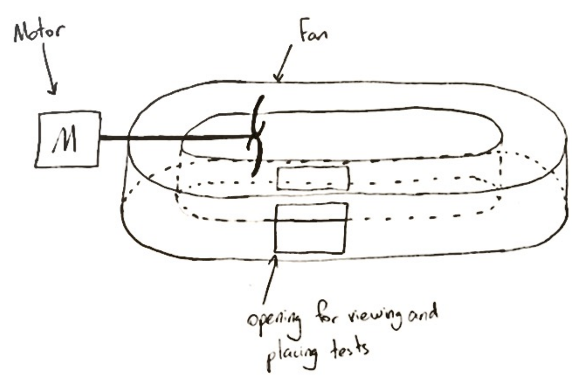

Figure 7: Closed loop wind tunnel for testing with constant VA density

For the pre-sensor chamber whether that be for the OPC-N2 or other dust sensors this testing rig will be very useful. For this I was thinking of a chamber with an inlet valve and outlet valve. The inlet valve will connect the air inlet of the airframe, and the outlet valve to the opening of the OPC-N2. Having VA build up in the chamber needs to be avoided and testing would validate the design.

4.0 SUSTAINABILITY ANALYSIS

This project brings many benefits to the social, environment, and economic impacts. Because NZ's primary form of international travel is using aircraft the effect of VA can have great impact on travel. Domestic flights also have the potential to get impacted. If people can't move around for business or travel they will suffer. If delay times were less, then people will be able to get to their destinations faster.

Socially this has a great impact as fears of a safety risks when flying, and having delayed flights can get very annoying passengers when needing to get somewhere. Having people worry about flying isn't good as it is already got enough worries. Having extra data available will give people peace of mind about flying with a VA risk.

With the presence of a VA cloud search and rescue operations may seize. Having the ability to have data about a VA cloud can give vital assurance of the for people's safety fears. Having search and rescue operating will settle people and they will not have to worry if they can operate.

The largest environmental benefit of having data will give specific bands of altitude available to fly in rather than diverting around the VA cloud saving a vast about more fuel. Another way this data can have a positive impact is from when the airplane can fly at a higher altitude. With the ceiling of a known altitude the plane can fly just below this altitude rather than being extra cautious and flying low. This difference in altitude will give a much greater engine efficiency. This is important because the amount of C02 released into the atmosphere will be significantly reduced.

The method we are using will allow us to recover the airframe after use. Typically, the airframe would just be abandoned into the ocean or earth but because of the price of the whole aircraft this is not viable. The batteries and electronics would be the most damaging to the environment as for the special metals used such as lithium and lead. Having a recoverable airframe will not put harmful objects in the environment.

The damage to the engine of an aircraft that VA can do is very large, so reducing this wear will reduce the amount of energy and materials used and wasted on engines. Repairing engines is also very expensive, which can have bad consequences for the airlines business. The materials used in engines are very expensive and take a lot of energy to produce.

Having grounded flights from a VA cloud can also wreak havoc for business people that rely on flying, causing large dips in the economy. For the Eyjafjallajökull volcanic eruption in 2010 the economic impact was estimated to 3.3 billon euro [7] which is a very large amount of money lost. This is important because jobs and projects could be lost, causing mass unemployment.

5.0 BUDGET SUMMARY

The total budget for this project is approximately \$2000 - \$3000 and has to include design and testing of the aircraft. Table 1 below shows the current costs and future costs in NZD.

ITEM	PRESNT COSTS	FURTURE COSTS	SHIPPING	TOTAL
GPS - COMPASS	100			100
PIXHAWK	200			300
OPC-N2	500		20	820
OPC-N2 SPI CABLE	120			940
TELEMETERY		300	20	1260
AIR FRAME		300		1560
SERVOS		200		1760
BATTERY		80	10	1850
TESTING WIND TUNNEL		400		2250
TESTING SENSOR CAMBER		100	10	2360
SAMPLER UNIT		130	10	2500
OPC-N2 PRECHAMBER		80		2580
ELETROSTATIC SENSOR		50		2630
BASIC DUST SENSORS		100	10	2740
AIR SPEED		80	10	2830

Table 1: Budget for sampling and sensing project

This total cost of \$2830 is within our price range, with the actual UAV costing \$2050.

6.0 Conclusions

This project has high hopes to achieve data up to 40,000 feet using a UAV ascending using a weather balloon, then descending under the power of gravity. NZ has a high chance of having air travel interrupted for VA clouds, and so the DTA has been assigned the task of coming up with a plan to minimize this effect. Satellite IR imagery can give good data on where the VA cloud is and specifically the direction and edge. But this data doesn't have any depth values so our project will be able to get specify where the VA is at discrete levels. This will allow for information to be given to airliners to fly at a set band to avoid the VA while not having to fly around the VA cloud.

With the events of Mount Sangeang and a Chilean volcano erupting and directly effecting NZ and neighboring nations this issue is real and needs attention.

For the project a low cost solution is needed that can go up to 40,000 feet and sense, collect and transmit data. A balloon that can carry a UAV that is of glider type will be sent up to measure particle size, density of present VA and collect a sample. Telemetry will then send the data captured to a ground station in case the UAV doesn't get recovered.

My two parts of the project are going well, the sampling unit and the sensor pre-chamber. The sampling unit concept is being finalized for testing, with testing relying on the closed loop wind tunnel. The NPC-02 has been brought and upon arrival work will start for designing a chamber to slow the air down in, before it draws it in its self.

The UAV airframe will be chosen after all other tasks have been completed. NIWA have lent us their airframe to us for setting up the various systems on board. But a larger plane will likely be needed.

7.0 References

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[4]M. Bursik, R. Sparks, S. Carey and J. Gilbert, "The Con- centration of Ash in Volcanic Plumes, Inferred from Dispersal Data", *United States Geological Survey*, pp. 19–29, 1991.

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[7]M. MAZZOCCHI, F. HANSSTEIN and M. RAGONA, *THE 2010 VOLCANIC ASH CLOUD AND ITS FINANCIAL IMPACT ON THE EUROPEAN AIRLINE INDUSTRY*. CESifo Forum, 2010.

8.0 Appendix

8.1 Appendix 1

```
clc,clear,close all

mass_needed = 0.5e-6;        % kg
speed = 5;                   % m/s
opening = 0.01:0.001:0.05;   % m
density = 4e-6;              % kg/m^3

area = pi*(opening./2).^2;   % m^2

flow_rate = speed*area;      % m^3/s

time_open = mass_needed./(density*flow_rate); % s

plot(opening,time_open/60)
title('Time per sample in relation to sample landing area')
ylabel('Time open (min)')
xlabel('Diameter of landing area (m)')
grid on
```