UNIVERSITY OF CAMBRIDGE

Centre for Climate Repair

INTERNSHIP REPORT

ON

QUANTIFYING MARINE CLOUD BRIGHTENING

By

Hongyan (Luca) Lin

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Centre for Climate Repair
Department of Applied Mathematics and Theoretical Physics
Wilberforce Road, Cambridge, CB3 0WA

Acknowledgments

I would like to express my sincere gratitude to Professor Hugh Hunt for kindly supervising my research internship on marine cloud brightening this summer. His insights into the work and his support in connecting me with experts in the field have been invaluable.

I am grateful to Dante McGrath and Jake Chapman at the Centre for Climate Repair for introducing me to the current state of marine cloud brightening research and for demonstrating the working principles behind the laboratory equipment. Their guidance has greatly contributed to the development of my work on portable sensors.

I would like to thank Jessica Girdwood (University of Manchester) for generously sharing her expertise in internal-flow optical particle sensors and her in-depth research on external-flow optical particle sensors. Her input has provided a crucial perspective and has helped shape the future direction of this project - particularly in guiding my plans for polarimetric measurements in my upcoming final-year project.

Many thanks to Graham Spelman and Matthew Oakes from Limosaero Ltd., who introduced me to the working principles of their solar-powered, long-endurance UAV and provided valuable advice on drafting requirement documents for the downselection of sensors.

Finally, I am deeply appreciative of Natalie Selwood, whose swift and reliable administrative support made my internship run smoothly. Her help has been consistently invaluable.

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Introduction

1.1 Objective of the Internship

Marine cloud brightening is a process that involves seeding marine low-level clouds to increase their reflectivity, hence cooling the earth. This internship aims to explore possible ways to monitor the process and the result of marine cloud brightening by focusing on three research questions. What are the possible sensors that could be used to measure the size distribution of sub-micron salt crystals and saltwater droplets in a diameter range approximately from 50 nm to 800 nm? What are the possible equipment that could be used to quantify the change in the cloud droplet size distribution? How can one quantify the Albedo change due to marine cloud brightening?

The first question aimed to validate the current plume dispersion models used in marine cloud brightening. The data would help to develop a newer and more accurate model of the rising salt plume. The diameter range of the final salt crystals was chosen to be between 50 nm to 200 nm as this was predicted to result in the most effective cooling effect (Wood, 2021). The second and third questions aimed to quantify the effect of future marine cloud brightening field experiments, which would benefit from more data to reveal more accurate results.

Apart from these three main research questions, the author also reached out to Limosaero to learn more about their solar-powered fixed-wing unmanned aerial vehicle (UAV), as shown in Figure 1 on the next page. This includes helping with the launch and recovery of the UAV, and developing a simple data visualisation software to have a deeper insight into the data logging onboard UAVs.

1.2 Scope and Methodology

Recent advancements in UAVs have made it possible to achieve aerial measurements with more agility and at a lower cost than traditional missions using manned aircraft. Quadrotors and fixed wings were both explored as viable options. Quadrotors have the benefit of being portable, easy to operate, and they can lift off from more places (picture of DJI Matrice 30T in Figure 2 on the next page). A fixed-wing UAV has a much larger payload capacity and, with Limosaero's solar-powered UAV, a much longer flight time as well.

Literature reviews and market research were carried out. They focused on finding how to quantitatively measure the salt aerosol size distributions in the specified diameter range using UAVs, as well as exploring the possible ways to measure the microphysical properties of clouds, including effective radius, effective variance and optical thickness. A requirement document was created to help with the downselection of sensors.

Python was used in the data visualisation exercise to create interactive plots for the example data provided by Limosaero.

1.3 Wider implications of your work

This work was part of the marine cloud brightening project and was supervised by Prof. Hugh Hunt. The insights coming out of this report will be helpful in future work done in the research group, including a fourth-year project where the author will continue this project, from October 2025.

It is expected that the data obtained from the work will advance the ability to quantify the effect of marine cloud brightening. It will also be able to address public concerns about marine cloud brightening and geoengineering better by providing higher-quality measurements.

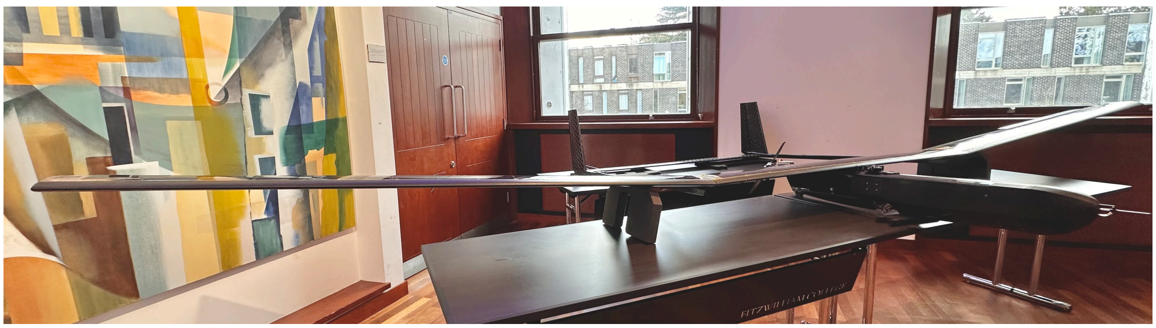

Figure 1. Limosaero UAV.

Figure 2. DJI Matrice 30T (Source: DJI).

Details of Internship Work

1. Internship Schedule

I contacted Limosaero Ltd. and spent the first 2.5 weeks getting to know more about their solar UAV, took part in two test flights of the UAV, and practised writing a Python data visualisation software. Their UAV has a large payload capacity, which enables larger payloads that are more capable. I used the opportunity to learn how to use a requirement document to help with sensor selection, the rigorous pre-flight safety checks, flight planning and post-flight debrief. This paved the way for my MCB payload research later. I was supervised by Graham Spelman from Limosaero and Prof. Hugh Hunt from CCR.

I spent the rest 5.5 weeks developing quantitative measurement techniques for marine cloud brightening under the supervision of Prof. Hugh Hunt. I first went through the literature and identified the use of lightweight sensors in aerosol size distribution measurement, as well as cloud microphysical property measurement. I then talked to experts in the field of airborne measurements, as well as reaching out to the companies that manufacture the lightweight sensors. I was then able to develop a good understanding of airborne measurements and suggested two possible ways to make lightweight in-situ measurements of salt size distribution and two possible ways to measure the cloud microphysical properties. I was also able to identify a suitable project for my fourth-year project at Cambridge, which involved using polarimetric measurements to derive the microphysical properties of coastal fogs as previously demonstrated in a manned research plane (Pörtge et al., 2023).

2. Selection of Candidate Sensors

A requirement document was created to help with the down selection of sensors and is available as a separate attachment. A selected list of candidate sensors for both the aerosol size distribution and cloud microphysical property measurement, with key numbers, is available on the next page.

It is worth noting that both POPS and Partector 2 Pro are internal flow optical sensors, and the accuracy of their reading depends on the flight condition, which could vary, according to a meeting with Jessica Girdwood. Jessica has developed open flow optical particle counters (OPC) as part of her PhD, which could have better performance than the traditional internal flow OPC (Girdwood, 2023). It could be beneficial to develop a new open flow OPC for use in measuring the salt aerosol size distribution in the context of marine cloud brightening.

The mSEMS + aMCPC combination is akin to a miniaturised lab-grade particle size distribution measurement device. They work like a differential mobility analyser (DMA) and a condensation particle counter (CPC). They could offer better performance at the expense of a higher price.

Table 1. Candidate sensors for salt aerosol size distribution measurement.

Name	Range	Weight	Price
DMS500 particle analyser by Cambustion	5 nm to 1,000 nm or 5 nm to 2,500 nm	Not available. But too heavy for an UAV.	On the order of £100,000
POPS	130 nm to 3 μm, 12 bins	600 g	Approx. USD 22,400
mSEMS + aMCPC	5 nm to 420 nm	2.3 kg (fixed wing only)	Approx. USD 58,800
Partector 2 Pro	10 nm to 300 nm	415 g	Approx. CHF 12,900

For the detection of cloud droplet sizes, which quantitatively verifies how much does spraying of salt particles affects the low-lying clouds over the ocean. One could either use a similar open flow OPC, like a cloud droplet probe provided by Droplet Measurement Technologies. However, a more powerful, agile and lightweight solution is available. Staying in the field of optics, one could use polarimetric imagery in the cloud bow scattering region to infer the effective radius and effective variance of cloud top droplets (Pörtge et al., 2023). Figure 3 below shows an example retrieval of the effective radius. This method uses a lightweight camera manufactured by LUCID Vision Lab that weighs about 100 grams and costs about USD 5,000. It's also convenient to obtain the measurement with the help of a Raspberry Pi, making it ideal for deployment on more kinds of UAVs in more scenarios, as well as an ideal candidate for my fourth-year project.

For the cloud Albedo measurement, it is best obtained via direct measurement using an albedometer onboard a UAV.

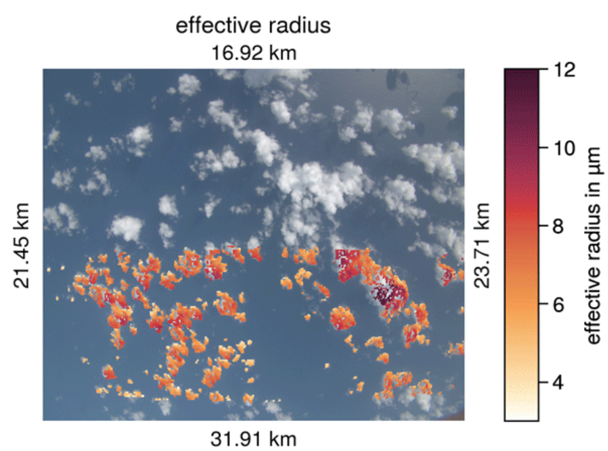

Figure 3. Example retrieval of effective radius (Pörtge et al., 2023).

3. Proposed Polarimetric Coastal/Valley Fog Measurement of Cloud Bow

This was identified as a more feasible fourth-year project to be carried out within the six-month time frame for the potential simplicity and portability of the hardware. Focusing on and completing this project will bring a new measurement technique to the MCB research that will allow high spatial resolution measurement of both the larger and smaller marine clouds.

As cloud microphysical properties can only be obtained when an UAV is legally allowed to fly above clouds, valley and coastal fogs are the two main scenarios where a simple UAV setup can be tested without additional certification. Polarimetric imagery of coastal fogs may be a better solution due to a relatively better-connected transport network and seasonal appearance of the coastal fogs. I have personally seen one near Scarborough Castle in December 2024, and it's relatively common to have coastal fogs in the UK. A list of potential sites for legal flights above the clouds is attached on the next page.

Possible sites identified for low-lying clouds/valley fog

- Peak District (Mam Tor / Rushup Edge & Winnats)
- Peak District (Shining Tor from Cat & Fiddle / Cats Tor)
- North Pennines (Great Dun Fell)
- Fort William, Scotland (Ben Nevis and the nearby mountains)
- Aviemore, Scotland (Cairn Gorm area via Cairngorm Mountain Funicular)
- Brecon Beacons, Wales (Pen y Fan)
- Lake District, England (Red Screes)

Possible sites identified for coastal fog

- North Yorkshire coast (Whitby, Ravenscar, Robin Hood's Bay, Scarborough, Flamborough Head)
- Seven Sisters Cliff and the nearby regions
- St Bees Head (on the west coast)

Possible UAV configuration

- Limosaero solar UAV with the LUCIS Vision Lab polarisation camera mounted on a custom gimbal and plenty of payload weight margin.
- A DJI Matrice 30 with the LUCID Vision Lab polarisation camera mounted on a custom pitch axis gimbal that could be attached to the landing legs of Matrice 30, with little payload margin.

The first UAV configuration offers a longer range and is ideal for long-duration monitoring of the clouds. The second UAV configuration with the DJI Matrice 30 is more portable and less complex, making it more suitable for shorter proof-of-concept missions. Given the tight timeframe, the author has identified that the second UAV configuration is more suitable in the short term.

For the second configuration to work, a Raspberry Pi and two motion sensors will be attached to the Matrice 30. The two motion sensors (red in the sketch shown in Figure 4) will sync the custom pitch gimbal with the remotely controlled DJI 3-axis gimbal. The latter also has a laser range finder, which could be useful to work out the distance of the cloud and hence the scattering angle measured at each point of the cloud.

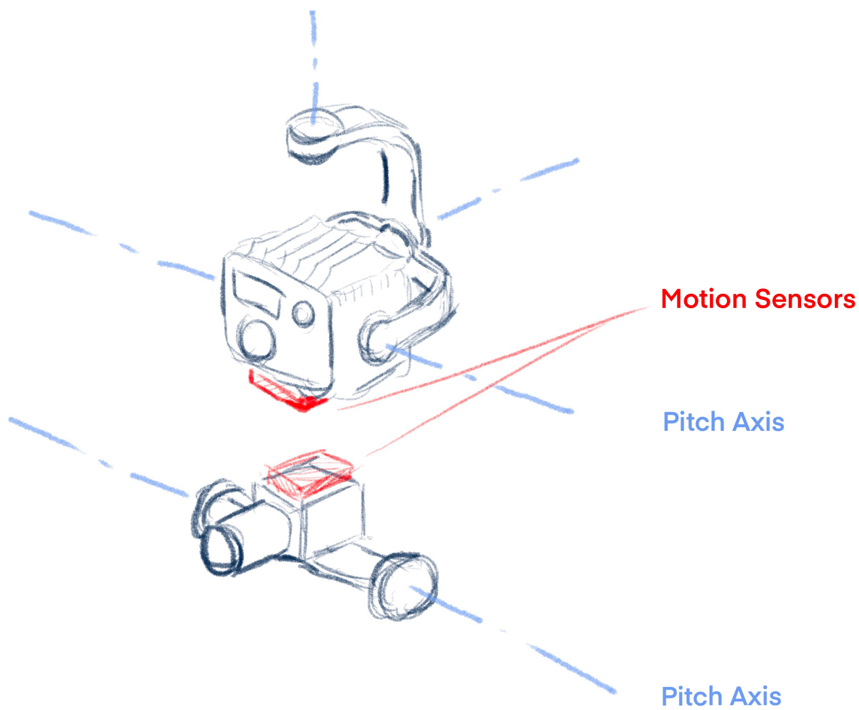

Figure 4. Sketch of pitch angle syncing of cameras (upper: DJI remotely controlled gimbal, lower: custom gimbal that follows the DJI gimbal).

4. Framework for data analysis

The internship did not involve intensive data analysis due to mostly working in the early stage of the project. However, I was able to perform data analysis, including grouping, clustering and implementing custom data analysis on the example data logged on the Limosaero UAV.

The proposed fourth-year project of polarimetric measurement of coastal/valley fogs will require additional data processing. This project proposes to use a polarisation camera to take measurements in the cloud bow scattering region, where the information regarding the cloud droplet effective radius and effective variance lies (Pörtge et al., 2023). This project would require implementing the look up table method (LUT) and also assuming the cloud droplet size follows a gamma distribution, which was used by Pörtge et al. (2023), and/or use a method called Rainbow Fourier Transform (RFT) as suggested by Alexandrov, Cairns & Mishchenko (2012), which doesn't assume a gamma distribution on cloud droplet size. But the RFT method comes with a drawback of requiring a higher angular resolution of the polarimetric measurement of the cloud bow (Alexandrov, Cairns & Mishchenko, 2012). Additional direct measurement of cloud droplet size could be carried out as a benchmark to test the indirect measurements.

5. What initial conclusions were made, and how did this frame the rest of your internship?

I have come to several findings during this internship. I noticed quite early on that the UAVs could not carry too much weight, and that the traditional aerosol size distribution sensors that are composed of a differential mobility analyser (DMA) and a condensation particle counter (CPC) are too bulky and too heavy to be carried on a UAV. This shifted my focus to research on laser-based sensors later during the internship and led to a few valuable discoveries.

In the meeting with Jessica Girdwood, I also learned that optical particle counters that measure the size distribution are less likely to perform well on a UAV if they are using internal flows. The aerosol could have deposited along the channel, degrading the measurement accuracy. I have also learned that developing an open flow optical particle sensor for this application may require more than six months. Based on this piece of information, I shifted my focus towards finding the possible ways to implement polarimetric imagery to retrieve cloud microphysical properties, which can equally contribute to the marine cloud brightening work Prof. Hugh Hunt is working on.

6. Did you encounter any issues with your research during your internship?

The relatively high price and the long lead time (6-12 weeks) for the sensors meant that I could not buy and test the sensors within an 8-week internship. The math in light scattering and the Rainbow Fourier Transform also required me to spend extra time in order to prepare. But this internship has laid the foundation for future work to be carried out and has certainly started to bridge my knowledge gap between mechanical engineering and marine cloud brightening.

7. Were there limitations to your work?

Due to the short duration of the internship, I was not able to obtain and process real data, either for salt crystal/saltwater droplet size distribution, or the polarimetric measurements of cloud bow. The methods introduced in this report are based on the literature only.

The options to carry sensors into the air may not have been exhausted. It is possible to carry sensors into the air using other means, like a tethered balloon. The payload weight limitation may not be as strict when other carriers are considered. I have listed the most economical solutions I could find.

Recommendations

The polarimetric imagery measurement of the cloud bow remains the most economically feasible option, and it is something manageable in the upcoming six-month fourth-year project. It is recommended that both the lookup table (LUT) method and the RFT method be looked at and compared against a direct measurement of the cloud particle size distribution.

It is recommended to carry out a comparison of a commercially available optical particle counter, like POPS, with a lab-grade size distribution counter, like a combination of DMA and CPC.

It'd also be worth exploring if an open-flow optical particle counter could be made to measure the size distribution from 50 nm to 400 nm, a size range not achievable by the UCASS made by Girdwood (2023).

Conclusion and Learnings

For the airborne measurement of salt crystal and saltwater droplet size distributions, it is best to develop an open flow optical particle counter (OPC) that's capable of measuring size distributions down to 50 nm. Alternatively, internal flow OPCs, like POPS, could be used with careful control of the inlet flow. The inlet flow control includes certain airspeed, angle of attack and yaw.

For the albedo measurement, it is most convenient to bring an albedometer with a UAV.

For the cloud microphysical property retrieval that examines how effective cloud seeding with salt aerosols is, one could either try to fly a UAV directly through a cloud with a cloud droplet probe (caution, this is sometimes against the law) or use optical remote sensing like polarimetric imagery in the cloud bow region. The latter requires either special permission to fly above clouds lying 1 - 3 km above ground or finding suitable low-lying clouds near the ground. However, it has the potential to reveal detailed cloud droplet size distribution. It could also show multiple peaks of cloud droplet size distribution when the data is processed with RFT.

When a UAV is used as the carrier for the sensors, either a quadrotor or a fixed-wing aircraft could be used. A fixed wing offers a longer range and can complete a longer monitoring mission. A UAV has the benefit of being portable and can be used in the preliminary work that validates the sensor and the math.

It is also a good opportunity now to reflect on this past internship, from which I learned and progressed a lot. I started with limited knowledge of cloud physics and optics. Marine cloud brightening (MCB) used to be a rather new concept for me. I was able to start researching to try and fill my knowledge gap, and kept going. And I have now understood more about marine cloud brightening and the various ways a UAV could help in airborne measurements.

At the beginning of this project, I was a complete beginner in MCB. I began my research by starting with some UAV work, which I am relatively familiar with. This got me into the world of airborne measurements using UAVs and got me started on finding the research questions of the otherwise rather open-ended research topic of "measure the process and the effect of marine cloud brightening".

Before I was able to begin my search for sensors, I was worried about not knowing what to look for. I reached out for help, and I was advised to make a requirements document, which I later found to be very useful.

During the project, when I put together a large pool of possible sensors, I was faced with a situation of not knowing which one to choose. Having a meeting to discuss this with experts in this field, including Jessica Girdwood from the University of Manchester, helped to solve a lot of question marks on the project.

Towards the end of the project, I found myself running out of time. It was unavoidable that I would have to wait for the sensors to arrive due to the long lead time. But looking back, if I were to do this again from the beginning, I believe I would have spent more time constructing a clearer project proposal at the beginning. It would be great to stay balanced when researching the size distribution sensor and the techniques to measure cloud microphysical properties. It would also be great to seek experts' advice a little earlier so that I could focus on polarimetric measurement earlier. I might then be able to have the time to work on some example data from the specMACS experiment (Pörtge et al., 2023).

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