Vertical Ozone Profiles in the Uinta Basin and Validating Drones as an Air Measurement Platform

Applicant

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Matching Funds: 37% of total project cost ($28,000 UofU + $26,700 WSU = $54,700)
Proposed Project Period: 7/1/2020 to 6/30/2021

Scope of Work

Abstract

We propose in situ ozone measurements resulting in vertical profiles using a minimum of two flight platforms and two sensor systems. High altitude balloons will measure from ground level to the mid-stratosphere carrying an industry standard ozonesonde. The balloons will also carry AtmoSniffers, an air sensor payload being developed inhouse. In addition, rotary-wing drones will be flown with similar air sensor payloads. This project has four primary goals: (1) Study upper-level transport of ozone above the Uinta Basin, (2) Determine the flight characteristics and air flow dynamics of drones used for air quality measurements, (3) Validate the drone measurements against the balloon borne measurements, (4) Determine if drones with lightweight air sensor payloads can reliably measure air pollution vertical profiles in the lower atmosphere.

Balloon-borne ozonesondes are considered the gold standard in ozone measurements and have been in use since 1934. However, not only are balloons personnel and time intensive, they are also at the mercy of wind conditions. On the other hand, a drone platform is easily maneuverable, can target predetermined air columns in a matter of minutes using only two operators. Drones are limited by FAA regulations but a waiver can easily be applied for. Drone fights will be conducted both with and independently of the balloon flights. The drones will carry sensor payloads close to the balloon flight path at launch and, when possible, at landing. Independent drone flights will also be conducted in close proximity to ground sensors to establish measurement baselines. A unique feature of our work is the use of drones and computational fluid dynamics (CFD) simulations to (1) quantify uncertainty in drone sensor measurements, and (2) correct drone measurement in light of said uncertainty. Recent evidence by PI Saad shows that the drone propeller wash can change the air measurement results for reasons that are still being characterized. These CFD simulations will serve as a model to inform effective ozone-sensor placement on the drones for accurate quantification of vertical ozone profiles in the lower troposphere.

Findings from this work will help our understanding of air exchange processes and pollutants mass transport and validate drones as a measurement platform for that task. The proposed work is collaborative between the University of Utah and Weber State University. It includes $28,000 in matching funds from PI Saad and $26,700 from CoPI Sohl and leverages existing equipment

(drones, sensors, compute nodes, etc…), simulation software (the Wasatch open-source code), and work currently being conducted by both PIs.

Basis and Rationale

Ozone has been a serious problem for Utah in both the Uinta Basin (mostly wintertime) and along the Wasatch front (mostly summertime) with exceedances of the 8-hour federal standard for ozone (70 ppb). Although the Wasatch Front is currently designated as a “Marginal” nonattainment area for ozone, recent DAQ measurements suggest that it is likely to be bumped up to “Moderate” with an attainment date of 2024. Emission control strategies will therefore need to be developed to bring the area into attainment. Regulating ozone levels is, however, complicated by the fact that ozone is derived from multiple sources including long distance transport, stratospheric intrusions, and biogenic and anthropogenic emissions, among others. **We propose in situ vertical ozone profile measurements from ground level to the mid-stratosphere to develop a better understanding of ozone layers and evolution over Utah**.

However, obtaining full profiles along the Wasatch front is complicated by the exceptionally busy airspace in the Wasatch Front airshed. FAA regulations severely limit balloon and drone flight measurements within five miles of any airport or heliport. There are two loopholes for the use of drones. FAA regulations allow drone flights to be higher when close to an obstruction such as an antenna. There are multiple radio antenna sites along the Wasatch Front with altitudes of typically 200 to 450 feet. The FAA regulations allow for flights as high as 400 feet above the obstruction, although that would likely be reduced given our complex airspace. Thus, drones can potentially be used to make vertical profile measurements along the Wasatch Front up to 850 feet above ground level with coordination with the FAA. An altitude waiver for FAA regulation Part 107.51(b) can be applied for as well. Depending on the location, the FAA has a track record of granting such waivers to allow for flight in the range of 600 to 1000 feet AGL. In more rural areas, such as the Uinta Basin, it is possible to apply for a waiver to 1500 feet AGL. Without a waiver, drones can be used to obtain vertical profiles near several towers in the basin that have heights of 215-329 feet. (Most of those are in controlled airspace and would need approval to fly the full 400 additional feet that is normally allowed without a waiver.)

Thus, drones could potentially be used to make rapid vertical profile measurements in both the Wasatch Front and the Uinta Basin. To do this, we need to have confidence in both the drone and the sensor system. **We propose to do multiple flights with drones configured with different sensor systems and close to well calibrated systems (such as the balloons) to validate the drone as a measurement platform.**

The drones will carry sensor payloads close to the balloon flight path at both launch and landing locations. Additional drone flights will be done at both in the Uinta Basin and in the Salt Lake City -- Ogden area. These flights will be intended both for real data collection and for testing of the drone as a measurement platform. We anticipate completing five full balloon/drone flights and at least ten drone flights independent of the balloons. For logistics reasons, the balloon flights will be between July and October, 2020, with at least one flight as a project wrap up in May-June of 2021.

The high altitude balloon flights will use a NOAA standard ozonesonde along with an AtmoSniffer sensor payload. The AtmoSniffer is a custom gas measurement system being developed at WSU. The AtmoSniffer measurements include O3, NO2, CO, CO2, SO2 and PM2.5 in addition to the standard meteorological data of pressure, temperature, and humidity. We anticipate carrying similar payloads under the drones, depending on weight and stability requirements for the drone.

The drone flights serve multiple purposes. The primary purpose is to test drones as a platform for air quality measurements. Evidence exists that the drone prop wash can change the air measurement results for reasons that are still being characterized. This is why the drone flights will track the balloon flights to as high an altitude as possible so that we can have comparison data. The drone flights can also fill in more details about the air quality in the bottom few hundred feet of the air column. We will work with the FAA to obtain a flight waiver for as high as possible so that we can better understand ozone transport in the lower planetary boundary layer. As noted above, the FAA tightly controls drone flight altitude. In the Basin we can obtain 400 feet without a waiver and possibly as high as 1500 feet. Along the Front it will depend on location, near antennas we can easily reach up to 400 feet without a waiver and possibly as high as 1000 feet with a waiver in locations that are outside of normal flight paths.

In summary, the proposed work addresses two primary issues: (1) obtain vertical ozone profiles, and (2) the design of sensor systems for mounting on drones to measure ozone in the lower troposphere. Both of these directly address issues in the UDAQ RFP section on “Air Exchange Processes and Pollutants Mass Transport.”

Vertical Ozone Profiles

Most ozone measurements are from one of two types of instruments: satellites and lidar. Both are expensive. Satellites provide global coverage, but only full column ozone totals. Lidar (typically differential absorption lidar, or “DIAL”) has vertical resolution but is difficult to move. The gold-standard is the ozonesonde, but those are personnel and time intensive while providing only a single measurement in time. According to the World Ozone and UV Radiation Data Centre (https://woudc.org/home.php) there are very few ozonesonde measurements anywhere near Utah. Thus, the WSU HARBOR ozonesonde measurements will help fill a data void. (As part of this project we will be submitting all our data, past and present, to WOUDC.)

The WSU HARBOR research team has made nearly twenty ozonesonde measurements since 2012. Most of these show ozone layers at ground level and in the stratosphere, but also numerous cases of intermediate layers. We want to better understand these layers and how they move.

Stratospheric ozone is primarily generated above the tropics via photochemistry as described by the Chapman rate equations. Global air currents transport this stratospheric ozone to the mid and upper latitudes both north and south. Large scale downdrafts generated by Brewer-Dobson circulation cells are believed to transport some of that ozone into the troposphere, possibly to ground level. Langford, et al, estimate that stratospheric ozone intrusion contributes up to 13% of the ground level ozone in Los Angeles, CA. Hocking, et al. [1] found frequent events of stratospheric-tropospheric ozone transport that reached ground level in southeastern Canada. At Weber State University, Dr. Sohl's HARBOR team has measured what appears to be ozone layer transport over the Uinta Basin. Here is an example dataset from 2013.

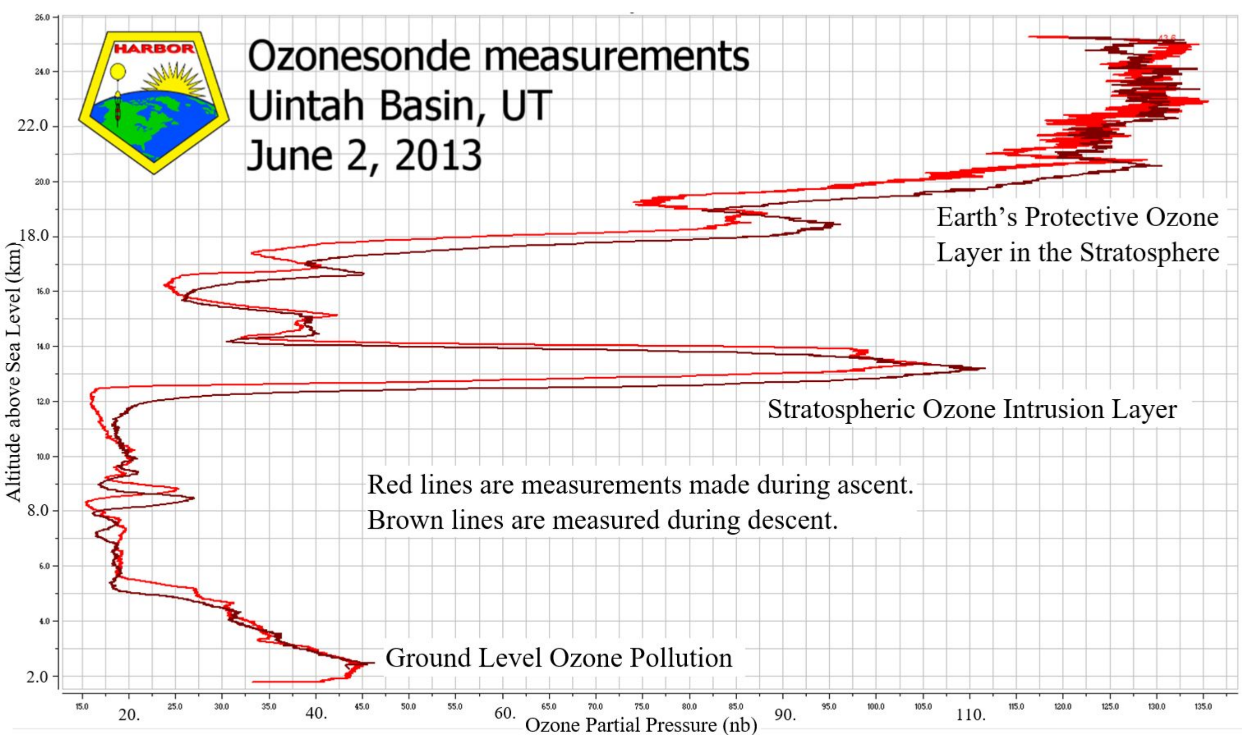

Figure 1: Ozonesonde measurements showing stratospheric and ground level ozone in addition to unexplained layers of ozone that could originate from Earth's ozone layer.

Intrusion layers reaching the ground are uncommon, but are an example of large scale transport that we hope to detect and possibly track.

Drone-borne Ozone Measurements

From 2012 to 2014 UDAQ funded the Uinta Basin Winter Ozone Study [3], a three-year project that measured ozone and precursor gases with high precision and fine time resolution at 19 fixed locations. The highest sensor was located at the Horsepool station at 14 meters above ground level. To really understand the mass transport of ozone and other pollutants we need to make measurements at significantly higher altitudes than 14 meters. The balloon-borne ozonesonde and AtmoSniffer will do this, but it is expensive, time consuming, and there is little control over the flightpath. Drones could potentially solve these problems.

Earlier studies by Dr. Tony Saad's University of Utah group have found measurement anomalies associated with drone rotor wash. To better understand this, some of the drone flights will track the balloon payload as close as safely possible, thus providing a calibrated dataset for comparison to the drone's dataset. Additional flights will concentrate directly on the drone as a measurement platform. This project will generate a **scientific basis for the effective placement and design of air quality sensors for use on drones as unmanned sensing vehicles**. In addition, data produced from this work will answer fundamental questions in the measurement and design of air quality sensors using drones:

1. What is the impact of rotors on measurements?
2. How feasible is it to use drones for air quality measurements in Utah?
3. Pending an FAA Certificate of Authorization (a flight rules waiver), how high can a drone reasonably be used for air measurements?

These added byproducts of this project will certainly provide a foundation for future air quality measurements using drones.

Meeting UDAQ Goals and Priorities

The proposed work meets the following goal and priority as specified in the RFP:

- Air Exchange Processes and Pollutants Mass Transport:
    - Long-range transport and stratospheric intrusion of ozone and its precursors.

Data collected by the drone(s) and balloons will provide information on meteorological conditions, and the vertical distribution of ozone and NO2 among other gases. These data can be used by UDAQ as part of the source inventory to inform policy and decision makers. These measurements will assist in understanding upper-level transport and evolution of ozone over Utah.

Technical Approach

The high altitude balloon measurements will be completed by the Weber State University HARBOR (High Altitude Reconnaissance Balloon for Outreach and Research) team directed by the CoPI. The HARBOR team has been flying research balloons over the Uinta Basin since 2008. We are developing a special air measurement system called the AtmoSniffer that measures multiple gases, particulate matter, and standard meteorological data (temperature, pressure, relative humidity, and wind). The AtmoSniffer is reaching maturity and should provide a solid dataset to complement the data from the ozonesonde that will be on each flight. The HARBOR ozonesonde includes an automated ground tracking station for live data download. The CoPI is an FAA licensed drone pilot (remote pilot certificate # 4268861).

Measurements

The WSU HARBOR team will complete at least five high altitude flights during the summer of 2020 and spring of 2021. Live ozone data will be collected from the ozonesonde and datalogged on the drone platform. Additional measurements will be done with the drone and compared to both ground based instruments and possibly a tethered aerostat.

The CoPI's long-standing expertise in measuring air pollution includes

- Participating in the 2015 Summer Ozone Study
- Participating in the 2016 Utah Winter Inversion Study
- Participating in the 2017 Utah Winter Fine Particulate Study
- Flight operations since 2008 with a 100% safety record in Utah, Idaho, Wyoming, Kansas, Colorado, and Nebraska.
- Development (patent pending) of the AtmoSniffer, a lightweight multi-gas air monitoring system designed for drone and balloon flight payload. Preliminary calibration runs at the UDAQ Hawthorne station show excellent correlation with UDAQ data.
- A NASA funded air measurement system is being developed specifically for smaller drones and balloons called the "Mini-Multi-Sensor Array" (Mini-MSA). Prototypes of this system will be used as part of this ozone study. The Phase II Mini-MSA will be flight ready by July 2020.

Simulations

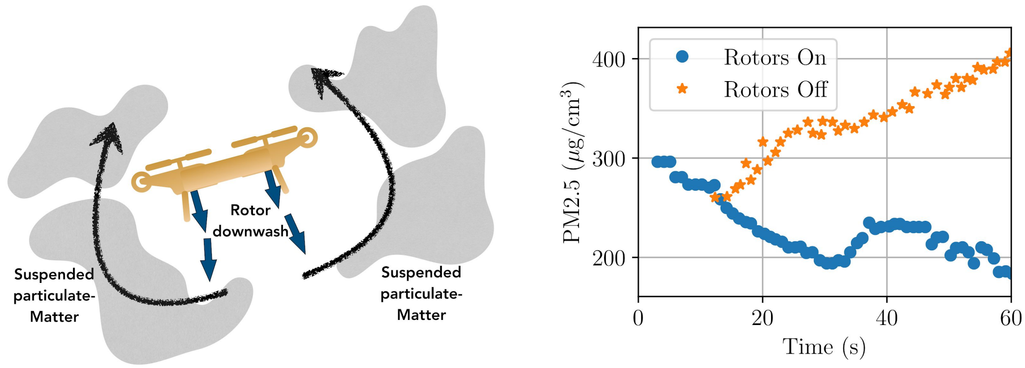

Figure 2: Left: Depiction of Brownout effect created by a drone. Right: Impact of drone rotors on sensor measurements of PM2.5 for diesel exhaust in a controlled chamber. Blue disks show concentration when drone rotors are turned on while orange stars show concentration when rotors are off (reference data).

A unique contribution of this proposal is the use of computational fluid dynamics (CFD) simulations to understand the impact of using drones on sensor measurements. We will conduct computational fluid dynamics simulations using in-house software developed by the PI to assess the airflow and particle and gas entrainement near a quadrotor drone. The purpose of these simulations is to evaluate the ideal placement of a sensor on a drone. Like helicopters (or any rotor driven vehicle) drones create a brownout region around them causing the surrounding air (including particles and gases) to move about in a complex manner. Such motion is likely to impact the measurements made by a drone-mounted sensor. Preliminary data collected from experiments conducted by PI Saad's group at the University of Utah [4] have shown a noticeable bias in measurements of up to an order of magnitude as shown in Figure 2.

Because experiments are (1) expensive, and (2) only represent limited conditions, PI Saad is currently developing a computational model using Computational Fluid Dynamics (CFD) to simulate the turbulent airflow around a drone. These simulations will be conducted using an in-house LES (Large Eddy Simulation) Finite Volume code, named Wasatch [5-7], that PI Saad has been developing since 2012. An example simulation of a quadrotor drone is shown in Figure 3 where velocity contours are shown. The end goal of these simulations is to inform the CoPI's measurements regarding the proper placement of ozone and other sensors on drones for the measurement of lower tropospheric pollutants.

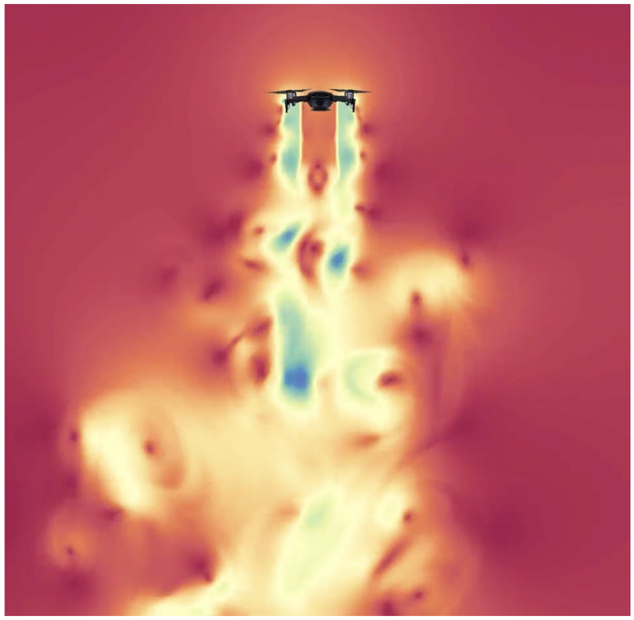

Figure 3: Velocity (speed) contours of the wake created by a drone showing complex and highly unsteady structures. For a video animation, see: https://youtu.be/5OarkRivY4M.

Expected Outputs and Outcomes

The following outputs and outcomes are expected from this work

1. Vertically-resolved ozone and NO2 measurements,
2. Improved understanding of the distribution and stability of stratospheric ozone and ground-level ozone in at least the lower 400 feet above ground level,
3. Quantitative data that supports state implementation plan (SIP) and emissions control development,
4. Comprehensive technical assessment of drone usage for accurate ambient ozone and general air quality measurements.

Findings from this work will help inform source emissions control development and will help support air quality models for SIP development.

Deliverables

Deliverables include:

- **Quarterly progress reports** to be submitted using the template and following the timeline specified in the RFP.
- A **final report** to include all of the components listed in the RFP.
  The project investigators will first develop a draft report and submit it to UDAQ for review within 90 days of project completion, as stated in the RFP. After receiving

UDAQ's comments and suggestions, the PIs will revise the report and submit it within a month, following the timeline outlined in the RFP.

- A **presentation** of the project findings at the 2021 "Air Quality: Science for Solutions" conference.
- **Data sharing:** Following the specifications of the RFP, all data to be shared will be made available within 8 months of project completion. Data will be housed on Google Drive. The University of Utah has access to Google's educational program which provides unlimited cloud storage. We will use this for archival storage of the data generated in this project, and provide external access to the datasets as needed. The Center for High Performance Computing at the University of Utah has verified that the Google storage solution is viable: it has adequate bandwidth to support uploading tens to hundreds of terabytes of data. We anticipate to share all measurements as well as the results of simulations.

Schedule

Vertical Ozone Profile Measurement Timeline

As soon as funding is released, development of attachment systems and lightweight modifications of the sensors for use on drones will be started. Drones will also be fitted with automated parachute systems for safety. Calibration will be finalized for the sensor systems. We anticipate flights starting within a month of the release of funds. Flight tracks typically become unstable as winter approaches, so all but one of the high altitude flights should be complete by October 2020. A final flight in late spring 2021 will allow final testing of the drone relative to the balloon borne ozonesonde. Data analysis will be conducted on the atmospheric data during Winter 2021 with preliminary results being presented at the 2021 Air Quality: Science for Solutions conference followed by a final report within 90 days of June 30, 2021.

Drone Studies Timeline

As soon as funding is released, we will start with two-dimensional simulations of drones to assess the effectiveness of the rotor model that we are using. We expect those to take up to 3 months (Oct. 2020). Next, a 3D model will be developed to reproduce the shape of the drones being used by the HARBOR team. We will input rotor speeds and ambient conditions and analyze the wake and turbulent structures created by the drone simulations. Simulations will be conducted at the University of Utah using PI Saad's compute nodes as well as one of the University's HPC clusters. As simulation data become available, we will inform the HARBOR team and also use those data to correct or validate measurements as needed.

	July 2020 - June 2021											
	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Task 1: Measurements												
1.1 Development of sensor mounting systems	■	■										
1.2 Parachute fitting and Sensor Calibration	■	■										
1.3 Flights		■	■	■						■	■	
1.4 Data analysis					■	■	■	■	■	■	■	
Task 2: Simulations												
2.1 2D Simulations	■	■	■									
2.2 3D Simulations		■	■	■	■	■						
2.3 Data analysis and validation	■	■			■	■	■	■	■	■	■	■
Reporting												
Quarterly reports			■			■			■			■
Final report												■

Figure 4: Proposed project timeline.

Budget

Budget Summary

Institution	Task	Matching	UDAQ
University of Utah Dr. Tony Saad	Project mngt, Simulation	$ 28,000.00	$ 50,560.00
Subaward: Weber State University Dr. John Sohl	Air Measurements, Flight Operations, Data Analysis	$ 26,700. 00	$ 41,902.50
Totals		$54,700.00	**$ 92,462.50**

University of Utah Detailed Budget

Personnel	Task	Time	Salary	Benefits	10% Indirects	Total
Tony Saad	Project mngt, Simulation	1 month	$9,883.11	$3,459.09	$1,334.22	$14,676.42
Hayden Hedworth	Simulation, Measurements	12 month	$23,949.37	$2,035.70	$2,598.51	$28,583.57
Total Personnel costs			**$33,832.48**	**$5,494.78**	**$3,932.73**	**$43,259.99**
WSU Subaward 10% F&A on $25k to UoU						**$ 2,500.00**
UofU Tuition Benefit						**$4,800**
Total U of U Budget						**$ 50,560.00**
Matching Funds						**$ 28,000.00**

Weber State University Subaward Detailed Budget

Personnel	Task	Time	Salary	Benefits	10% Indirects	Total
John Sohl	Analysis	0.5 months	$3,000	$ 1,500.00	$300	$4,800.00
Jeff Page	Measurements	2 months	$ 12,500.00	$ 6,250.00	$ 1,250.00	$ 20,000.00
Undergraduate Students	Construction & Flight Ops	10 hrs for 14 weeks	$ 4,500.00	$ 382.50	$ 450.00	$ 5,332.50
Total Personnel costs			**$20,000**	**$8,132.5**	**$2,000**	**$30,132.5**
Costs not subject to WSU 10% F&A						
Flight Costs						$ 10,000.00
Drone parachute						$ 670.00
Sensor hardware						$ 1,000.00
Zero air filters						$ 100.00
Total Other Costs						**$ 11,770.00**
Total Subaward Budget						**$ 41,902.50**
Matching Funds						**$ 26,700.00**

PI Saad will match up to $28,000 from his startup funds at the University of Utah to complement support for another Graduate student to assist in the simulations. CoPI Sohl will also match up to two additional months from his time valued at $26,700.

The budget includes support for 1 month of the PI time and 1.5 weeks of the COPI's time. It also includes support for 2 months for Mr. Jeffrey Page (air measurement engineer, Weber State). As for students, 12 months for a graduate student (Mr. Hayden Hedworth) and 10 hours/week for 15 weeks for undergraduate students from WSU. Tuition benefit is required by the University of Utah but is not subject to the 10% indirect cost rate negotiated with DAQ. Benefits are calculated at a rate of 50% for faculty and staff (Saad, Sohl, and Page) and at 8.5% for students (undergraduate students, and Hedworth). The flight budget includes costs of five balloon flights, 20 drone flights, and covers flights, transportation, vehicles, food, lodging, supplies, and expendables rated at $2,000 per balloon flight. Hardware costs are listed in the table and include a drone parachute, sensor hardware, and zero air filters.

Leveraging existing resources, expertise, and projects

The proposed work is a collaboration between the University of Utah and Weber State University. It includes $28,000 in matching funds from PI Saad and $26,700 from CoPI Sohl. The work leverages existing equipment (drones, sensors, compute nodes, etc…), simulation code (Wasatch code), and work currently being conducted by both PIs. Currently, PI Saad is conducting experimental and computational work to assess ideal sensor placement on drones [4]. In addition, CoPI Sohl has a long-standing record in measuring air pollution including

- Participating in the 2015 Summer Ozone Study
- Participating in the 2016 Utah Winter Inversion Study
- Participating in the 2017 Utah Winter Fine Particulate Study
- Flight operations since 2008 with a 100% safety record in Utah, Idaho, Wyoming, Kansas, Colorado, and Nebraska.
- Development (patent pending) of the AtmoSniffer, a lightweight multi-gas air monitoring system designed for drone and balloon flight payload.
- A NASA funded air measurement system is being developed specifically for smaller drones and balloons called the "Mini-Multi-Sensor Array" (Mini-MSA). Prototypes of this system will be used as part of this ozone study.

Personnel Roles and Responsibilities

PI Saad will be responsible for the overall direction of the project with a focus on the flight and simulations aspects of the work. CoPI Sohl will be responsible for directing the measurements and helping to analyze the data. PI Saad will supervise a Ph.D. student, CoPI Sohl and research staff member Page will supervise several undergraduate students. All students will be involved in the measurements. The student working with PI Saad will be primarily focused on computational fluid dynamics simulations. CoPI Sohl's staff and students will be focused on the flight operations and gas data analysis.

Dr. Saad (PI) is an assistant professor of Chemical Engineering at the University of Utah. He has extensive experience in modeling and simulation of multiphase reacting flows, computational fluid dynamics, and high performance computing. He is currently conducting research on the effectiveness of drones in measuring PM2.5, a project whose outcomes aim at developing tools to find optimal sensor placement on multirotor drones.

Dr. Sohl (CoPI), Brady Presidential Distinguished Professor of Physics, has over 40 years of experience with flight and airborne measurements. He has several patent filings for sensor systems and eleven years of airborne flight experience in the Uinta Basin. He is currently leading a team that is designing a portable air measurement system, the AtmoSniffer, that is nearly ready for commercial production. The AtmoSniffer prototype will be used in this project. Dr. Sohl is an FAA, part 107, licensed drone pilot.

Mr. Jeffrey Page, air measurement engineer, BSEET, has 19 years of experience in circuit design and development including high-altitude flight, air sensors, and embedded systems design. He has over five years of experience doing air sensor calibration.

Mr. Hayden Hedworth is a Ph.D. student in the department of Chemical Engineering at the University of Utah. He has been working under the supervision of Dr. Saad since 2019 and is co-supervised by Dr. Sohl. Mr. Hedworth is currently leading the effort on our drone project and will be responsible for conducting field experiments for the VOC, Ozone, and PM2.5 measurements on the drone. Mr. Hedworth will also be responsible for developing numerical simulations to assess the flowfield around drones and any attached sensors.

The Weber State University undergraduate students are all members of the HARBOR high altitude flight, outreach, and measurement team. They will be supervised by Dr. Saad, Dr. Sohl, and Mr. Page.

Citations

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[2] Langford, A. O., et al. "Stratospheric influence on surface ozone in the Los Angeles area during late spring and early summer of 2010." Journal of Geophysical Research: Atmospheres 117.D21 (2012).

[3] Utah DAQ Report: https://documents.deq.utah.gov/air-quality/planning/air-quality-policy/DAQ-2015-021002.pdf

[4] The Effectiveness of Drones in Measuring Particulate Matter in the Atmosphere. University of Utah Seed Grant Program. PI: Tony Saad.

[5] Saad, T., & Sutherland, J. C. (2016). Wasatch: An architecture-proof multiphysics development environment using a Domain Specific Language and graph theory. Journal of Computational Science, 17, 639–646.

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