CLOUD-MAP: Collaboration Leading Operational UAS Development for Meteorology and Atmospheric Physics

2019 Annual Report

NSF EPSCoR RII Track II FEC Award Number: 1539070

HEADING:
UAS in Atmospheric Physics
CLOUD-MAP: Collaboration Leading Operational UAS Development for Meteorology and Atmospheric Physics

Jamey Jacob, PI - Oklahoma State University (Oklahoma)
Phil Chilson, Co-PI - University of Oklahoma (Oklahoma)
Adam Houston, Co-PI - University of Nebraska (Nebraska)
Suzanne Weaver Smith, Co-PI - University of Kentucky (Kentucky)

Annual Report
NSF EPSCoR RII Track II FEC
Award Number: 1539070
Project Start Date: 8/1/2015
Report Submission Date: August 12, 2019
Reporting Period: 3/16/2018 – 3/15/2019

Compiled August 12, 2019.

This work is supported by the National Science Foundation under Grant No. 1539070, *UAS for Atmospheric Phsyics*, alternatively referred to as *Collaboration Leading Operational UAS Development for Meteorology and Atmospheric Physics (CLOUD-MAP)*, to Oklahoma State University in partnership with the Universities of Oklahoma, Nebraska-Lincoln and Kentucky. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Questions or concerns regarding content should be directed to the CLOUD-MAP PI, Prof. Jamey Jacob at `jdjacob@okstate.edu`.

This document was prepared in LaTeXpdfeTeX, Version 3.141592-1.30.4-2.2.

CLOUD-MAP: Collaboration Leading Operational UAS Development for Meteorology and Atmospheric Physics

Annual Report
NSF EPSCoR RII Track II FEC
Award Number: 1539070
Project Duration: 8/1/2015 – 7/30/2019
Reporting Period: 3/16/2018 – 3/15/2019

May 15, 2019

Executive Summary

The period of this report covers from March 16, 2018 to March 15, 2019.

In the year-long performance period, the team accomplished all of its objectives, including progress towards completion of the 4th year research goals, organization of the research and workforce development efforts, meeting with and generating input from the community of stakeholders, completion of the third flight campaign in collaboration with NOAA, NCAR, and international participants, and planning for the penultimate workshop, in addition to many individual technical and outreach related tasks.

The overarching goal of the project is to develop integrated small unmanned aircraft systems (SUAS) capabilities for enhanced atmospheric physics measurements. This team includes atmospheric scientists, meteorologists, engineers, computer scientists, geographers, and chemists necessary to evaluate the needs and develop the advanced sensing and imaging, robust autonomous navigation, enhanced data communication, and data management capabilities required to use SUAS in atmospheric physics. Annual integrated evaluation of the systems in coordinated field tests also requires advancing public policy related to adoption of SUAS technology and integration of unmanned aircraft into the airspace. CLOUD-MAP builds on the team members' and combined partners' existing expertise and capabilities in atmospheric and meteorological observations, SUAS development, and STEM outreach and education. A primary long-term impact expected from CLOUD-MAP will be the indelible multidisciplinary scientific and educational collaboration of the early-career faculty who are involved. In the duration of the project, collaborations have developed among team members leading to increased collaborative proposal development and subsequent collaborative publications.

I Development 1

1 NSF EPSCoR Specific Reporting Requirements 1
1.1 Overview . . . 1
1.2 Additional Major Project Elements . . . 2
1.2.1 Early Career Faculty Advancement and Interjurisdictional Collaborations . . . 2
1.2.2 Public Outreach . . . 4
1.3 Broadening Participation . . . 5
1.4 Expenditures and Unobligated Funds . . . 6

II Research Program 8

2 Highlights 8
2.1 LAPSE-RATE Flight Campaign . . . 8
2.1.1 Time response of measurement systems . . . 10
2.1.2 Trends and broader discussion . . . 10

3 Tasks Research Reports 13
3.1 Science Focused Objectives . . . 13
3.1.1 Mesoscale Storm Physics . . . 13
3.1.2 Storm Microphysics . . . 18
3.1.3 Airborne Soil Hydrology . . . 21
3.1.4 Local-Scale Temporal and Spatial Climate Variations Measurements . 23
3.1.5 Airborne Sampling Systems . . . 27
3.1.6 Atmospheric Infrasonic Sensing . . . 30
3.1.7 Multi-Scale GIS Correlation . . . 34
3.1.8 Evaluation of Profiling Observational Capabilities . . . 37
3.2 Engineering Focused Objectives . . . 41
3.2.1 Cooperative Control of Small UAS Formations For Distributed Measurement . . . 41
3.2.2 Integration of Spatially Distributed Data from Moving Sensor Platforms 43
3.2.3 Heterogenous Robot Control and Multi-agent UAS Simulators . . . 45
3.2.4 Robust Conformal Antennas for UAS Communication . . . 50
3.2.5 Persistent Monitoring . . . 51
3.3 Public Policy Focused Objectives . . . 55
3.3.1 Rapid Dissemination of Risk Information . . . 55

III Supporting Information 60

4 Data Outcomes Portal Report 60

Part I
Development

1 NSF EPSCoR Specific Reporting Requirements

1.1 Overview

During the reporting period of the program, the collaborative research team has achieved all of their planned objectives and are on schedule for achieving the remaining objectives in subsequent project years. At a high level, these include:

- Mentorship/traineeship of early career faculty and students including multi-jurisdictional collaboration on proposals and publications through team science;
- Better physical understanding of atmospheric physics and meteorological processes within the Earth's lower boundary layer;
- Improved instrumentation for measurement of meteorological and atmospheric physics (MAP) related phenomena;
- Development of and testing better small unmanned aircraft systems (SUAS) for use in MAP applications;
- Enhanced understanding of operational and logistical requirements to operate SUAS within the US for MAP applications;
- Knowledge of public perception of SUAS for scientific and other applications within the US; and
- Enhancing public awareness of the scientific and broader benefits of SUAS in weather and atmospheric studies.

These are summarized below and a full description of specific accomplishments from each of the research tasks is provided in §3.

The goal of the CLOUD-MAP project is to develop and test systems for remote and in situ sensing of Earth's atmosphere with an associate scientific goal of enhanced understanding of physical processes within the Earth's atmosphere. As such, primary objectives, shown in Figure 1 have been organized into four specific threads as shown in Table 1. In particular, systems will focus on the lower ABL. This region is beyond the height where data is obtained by surface observing stations, but below that sensed by most airborne weather systems, including balloons, aircraft and satellites. The importance of accurate data in this region is well understood - this region is a major factor in the development of many meteorological phenomena, not the least of which include severe storms.

The project leverages key expertise across the institutions, including unmanned aircraft systems, atmospheric measurement, robotics and autonomous control, and weather analysis and modeling. Each of these areas is critical for the research to be successful. Basic questions include the following: How can local data acquired by SUAS be used to better understand larger weather phenomena? Can SUAS be used to measure large-scale patterns and trends found in the atmosphere? What advancements in operational requirements are necessary to provide routine capabilities and confidence to use SUAS as a meteorological diagnostic tool? The questions are addressed in a progressive manner through cooperate research and development by the four partners over the 4 year period of the program as shown in Table 2.

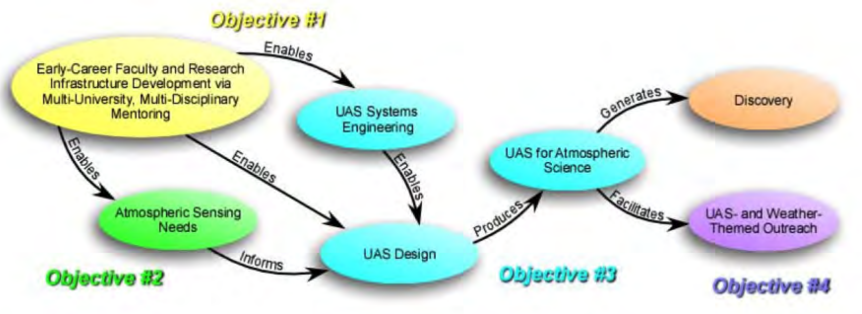


Figure 1: Research objectives.

Task	Abbreviated Title	Lead	Org	Year-1 Campaign
1-1	Program Management	Jacob, PI	OSU	Social Integration
2-1	Convection Initiation	Houston	UNL	Ref sensor eval
2-2	Storm-Scale Microphysics	Van Den Broeke	UNL	Collaboration
2-3	Airborne Soil Hydrology	Sama	UK	Ref sensor eval
2-4	Local-Scale Climate Measurements	Martin	OU	Collaboration
2-5	Airborne Sampling Systems	Guzman	UK	Sensor testing
2-6	Severe Storm Infrasonics	Elbing	OSU	Sensor testing
2-7	GIS Multi-Scale Correlation	Frazier	OSU	Equip testing
3-1	Cooperative Control	Hoagg	UK	Collaboration
3-2	Integration of Moving Sensors Data	Bailey	UK	Sensor testing
3-3	Heterogenous Robot Control	Crick	OSU	Platform testing
3-4	Multi-Agent Game Emulator	Crick	OSU	Collaboration
3-5	Robust Conformal Antennas	Ruyle	OU	Collaboration
4-1	Public Perception and Policy	PytlikZillig	UNL	Collaboration
4-2	UAS Workshops	Jacob	OSU	Collaboration
4-3	Rapid Risk Dissemination	Frazier	OSU	Collaboration

Table 1: Research tasks by initial responsibility including university and investigator.

1.2 Additional Major Project Elements

1.2.1 Early Career Faculty Advancement and Interjurisdictional Collaborations

Early career faculty advancement has proceeded well, with EC faculty participating at all levels within and without the project as indicated by the DOP results. To date, promotions

CLOUD-MAP	Year 1 2015-2016	Year 2 2016-2017	Year 3 2017-2018	Year 4 2018-2019
Science	Science tasks	Science tasks, plus 2017 Total Eclipse	Science tasks, plus science question	Science tasks, plus science question
Technology	Sensors/platforms	Sensors/platforms, plus 3-5 formation	Sensors/platforms, plus >10 formation	Sensors/platforms, plus 3-5 adaptive flight control
Community Interaction	Perception focus groups, plus outreach	Perception, plus severe-weather risk, outreach, PR	Perception, plus risk, outreach, PR	Workshop and outreach
Team Science via Flight Campaigns	Complimentary	Multidisciplinary	Interdisciplinary	Transdisciplinary
	Flights: 241 Flight hours: 25	Flights: >500 Flight hours: >70		
Collaborative Publications	Multidisciplinary conference: 5	Multidisciplinary conference: 6	Multi-university conference: 1	
	Multi-university conference: 2	Multi-university conference: 2	Multidisciplinary, multi-university journal: 3	

Table 2: Team science timeline.

to tenure have included 3 faculty obtaining tenure at the University of Kentucky, 2 at the University of Nebraska-Lincoln, and 3 at Oklahoma State University. Of the initial 11 EC faculty as part of the CLOUD-MAP program, 8 received promotion and tenure in their home departments during the course of the project, 1 is currently in the process of applying for tenure, and 2 were recruited by and left for other institutions.

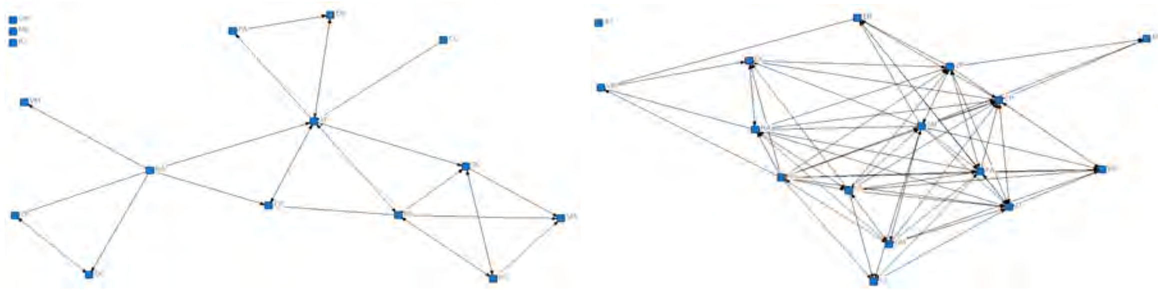
Table 3: Early career faculty promotions.

Year	**Early Career Faculty**	**Institution**
2016	Jesse Hoagg	University of Kentucky
	Carrick Detweiler	University of Nebraska-Lincoln
2017	Marcelo Guzman	University of Kentucky
	Matthew Van Den Broeke	University of Nebraska-Lincoln
2018	Chris Crick	Oklahoma State University
2019	Brian Elbing	Oklahoma State University
	Jessica Ruyle	University of Oklahoma
	Michale Sama	University of Kentucky

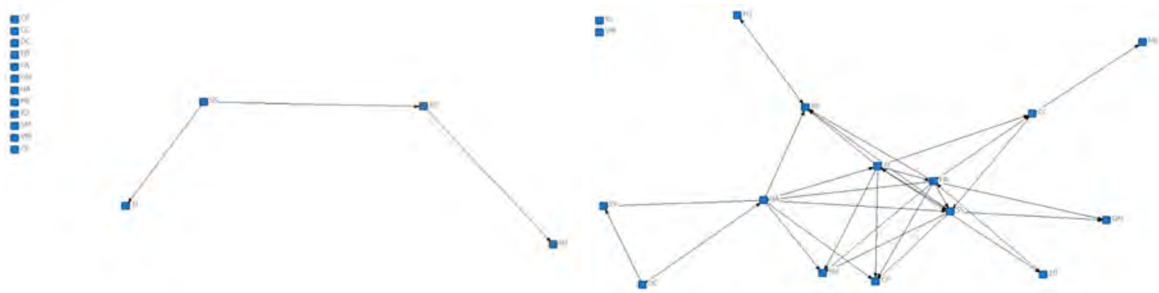
Collaborative proposals are highlighted elsewhere in the report indicating an increasing and high amount of research collaboration. Research collaboration, particularly inter-jurisdictional collaboration, among the project participants has been high exceeding expectations. Examining these numbers in more detail, before CLOUD-MAP , approximately 70% of the total faculty collaborations were intra-university. Even so, many of the CLOUD-MAP team had not worked together previously so there was capacity to grow internal collaborations as well as external ones. Collaborations between the team members has resulted in a substantial number of collaborative publications. A special submission for the journal *Atmosphere* was organized and edited by the team to highlight many aspects of this project, among others.

Utilizing our internal process, we have recorded and tracked collaborations among investigators across the project period. These detail the development of collaborative activities for every year of the project across different facets of the program. Collaboration in proposals, journal articles, and overall research are shown in Figure 2 for years 2015 and 2019 and demonstrate differences in research collaboration. For example, while all areas of collaboration have increased, it is clear that journal collaboration has increased the most while proposal development has developed a large degree of interconnectivity.

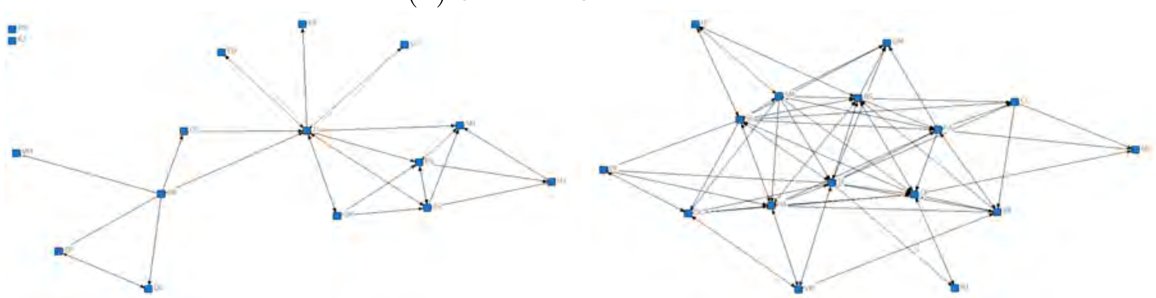
2015 2019



(a) Proposal Collaboration.



(b) Journal Collaboration.



(c) Overall Research Collaboration.

Figure 2: Investigator collaboration research map for 2015 (left) and 2019 (right) showing the evolution of the collaboration prior to the the start of the project to the current period.

1.2.2 Public Outreach

The PIs have given both general and technical presentations and seminars discussing the details and broad benefits of the NSF sponsored program. These include but are not limited to the American Institute of Aeronautics and Astronautics, the American Meteorological

Annual Summaries	Yr-0		Yr-1		Yr-2		Yr-3	
	Intra-	Inter-	Intra-	Inter-	Intra-	Inter-	Intra-	Inter-
Research	27	10	43	30	43	34	41	41
Journals	3	1	5	9	8	11	11	11
Conferences	8	1	11	6	9	21	21	27
Proposals	28	12	28	12	20	19	23	23
Totals	66	24	87	57	80	85	96	102

Figure 3: Years 1-3 products summary.

Society, the Association of Unmanned Vehicle Systems International, the National Center for Atmospheric Research, the National Weather Service and the National Severe Storms Laboratory, Friends and Partners In Aviation Weather, NASA, and the FAA. There has been a growing interest in UAS related atmospheric monitoring by various news outlets. We have provided interviews with several of the local newspapers, magazines, and news stations. There has also been attention from more widely recognized news outlets such as National Geographic, Popular Science, PBS News Hour, Weather Channel, CBS News, Physics Today, and others. The project was featured as part of the American Physical Society's annual meeting in Boston through APS-TV (`https://www.youtube.com/watch?v=zO4oQqWwvLg`) as well as featured on National Geographic's Explorer program. The team also presented to the White House Office of Science and Technology Policy as part of a Choctaw Nation event in Spring, 2019. Additional details on public outreach are provided in the research report.

1.3 Broadening Participation

The CLOUD-MAP team as a whole has been striving to recruit from underrepresented groups when selecting graduate and undergraduate students. Demographic information is collected by the team utilizing portions of the limited information provided by ILI Track-2 Data Outcomes Portal. However, due to some students under-reporting their information to ILI as well as those unwilling to disclose demographic data on the DOP, we have made an effort to gather this information through the students directly. This data is reported here for the current reporting period.

Over 100 recorded trainees have participated in the project over the current period with the majority of these students (over 80%) participating throughout the entire year. These trainees consist of primarily undergraduate and graduate students but also include K-12 (high school) students and post-doctoral researchers. The project has engaged undergraduate students at a substantial level with both integrated involvement in research projects (under direct mentorship of a graduate student) and with class-related and outreach projects. The number of undergraduate students actively involved in the project was so great that it exceeded the ability of the DOP to properly track the students working on the effort and required reprogramming on part of the DOP contractor. A small percentage also includes research staff, most of which transitioned from graduate student status to full-time employee during the project period. Over 20% of the students participating in the project are female. Racial and ethnic breakdown was harder to determine, since most students did not report that information on the DOP. Thus, best estimates were used based on information obtained by the universities. It is estimated that approximately 15-20% of participants are a member of an under-represented minority.

At OSU, over 50 trainees have been involved on the project (over 40 recorded on the DOP plus many others that have not). This is roughly equally split between graduate and undergraduate students. Additionally, 6 high school students worked on the project. Approximately 25% of total trainees were female and 13% were under represented minorities (African American and Native American). At OU, the current makeup of undergraduate students consists of 5 women and 3 men across both meteorology and electrical and computer engineering. For the current graduate students, all 6 are men. Two postdocs have been hired in the area of UAS research, both are women. They are not paid from CLOUD-MAP directly, but the funds being used to support them were secured in part as a result of CLOUD-MAP. Two of the three faculty supported by OU are women and have provided a role model for the students. We should note that electrical engineering is a male dominated field. Although not as extreme, the majority of students in meteorology at OU are also male. The UK CLOUD-MAP team to date is comprised of 5 faculty, 2 staff, and 26 trainees. Five of the 26 trainees and one new staff member were added this year. A large number of new trainees is anticipated next year after expected graduations of graduate and undergraduate students. Four of the trainees are female; one is an underrepresented minority. Additional details on diversity are provided in the research report.

As discussed elsewhere, several tasks include STEAM related outreach activities with the goal of broadening participation, which includes K-12 STEM and diversity enhancement. We have built on current STEM activities in Oklahoma, Nebraska and Kentucky to develop national K-12 activities. This include community efforts to obtain a better understanding of public perceptions of UAS applications to assist policy development concerning the potential widespread application of UAS for atmospheric science. Since Oklahoma, Nebraska, and Kentucky serve large rural populations and both Oklahoma and Nebraska serve large Native American populations, the project teams are using the research as a vehicle to serve these underrepresented groups working with Tribal Colleges to establish courses and programs to provide unique STEM related opportunities to underrepresented students. We use social media as one of our primary outreach mechanisms. In addition to our traditional website (cloud-map.org), this includes Facebook, YouTube and twitter posts and feeds to keep both team members and fans up-to-date with the progress of the program and will be used to promote STEM careers in atmospheric sciences, aviation, engineering, meteorology, and other related disciplines to K-12 students. Videos are being professionally developed to enhance the social media outreach efforts. Additionally, resources are aimed at encouraging undergraduate students to pursue graduate education. Additional details on STEM activities are provided in the research report.

1.4 Expenditures and Unobligated Funds

Overall project budget is within expectations of planned expenditures, with a burn rate projected to expend the total budget by the end of the project for each of the core university partners. Expenditures as of March are over 90% of the total 4 year budget, allowing just enough support for the remaining months of the effort. Note that funding numbers are only up-to-date as they are invoiced, so sub-contracting universities (OU, UNL, and UK) typically lag expenditures by a quarter or more, so individual breakdowns are provided below. Invoice lags notwithstanding, this is still expected to be on track of a total burn due in part to the large expenditures expected as part of the 2019 summer workshop (additional travel and support). Summer expenditures typically increase with trainees added for flight testing and conference travel, which will be a substantial portion of the 2019 budget.

Part II
Research Program

2 Highlights

2.1 LAPSE-RATE Flight Campaign

The highlight of the Year 3 effort was the joint flight campaign between the 4 university part years. For the first year, the flight campaign was part of a larger effort organized by NOAA and CLOUD-MAP team members along with additional government and academic partners. While CLOUD-MAP participants had the vast majority of personnel and observation platforms, inclusion of and collaboration with non-EPSCoR institutions was intentional and a realization of part of the proposed institutional development objectives.

As part of the most recent ISARRA (International Society for Atmospheric Research using Remotely-piloted Aircraft) meeting, hosted by the University of Colorado-Boulder (CU-Boulder) during summer 2018, a community field campaign was organized in which a primary scientific goal was the characterization of system and sensor performance for improving the quality of atmospheric measurements. The field campaign, titled **Lower Atmospheric Process Studies at Elevation - a Remotely-piloted Aircraft Team Experiment (LAPSE-RATE)** took place in the San Luis Valley of Colorado from 14–19 July, 2018, and included participation by a variety of university, government, and industry teams. Over the course of six days, more than 100 participants from 13 institutions and organizations supported the coordinated deployment of over 35 unmanned aircraft and completed 1287 flights, accumulating more than 260 flight hours. Flight operations spanned a large area of the San Luis Valley (approximately 3500 km^2), and distributed research flights were organized to observe several interesting atmospheric phenomena, including the morning boundary layer transition in a high-altitude mountain valley, the diurnal cycle of valley flows, convective initiation, and aerosol properties. The participants are shown in Figure 4 while details of the site and campaign logistics are shown in Figure 5.

In addition to these scientific objectives, coordinated missions were organized between the participating teams to compare measurements across sensors and platforms and validate these measurements against reference measurements from ground based instrumentation, in particular from a 18 m meteorological tower. The purpose of these intercomparisons was to not only compare the performance of different sensors to the ground-based references but also to compare sensor performance across platforms. The objectives of this study were to evaluate the measurements collected during intercomparison flights to provide a deeper understanding of the accuracy related to capturing atmospheric measurements via sUAS and to identify factors that may contribute uncertainties or error to meteorological measurements. We provide an overview of the site information, a detailed description of the sUAS and ground-based systems used for intercomparison as well as information on the flight patterns and analysis techniques and present the results of these comparisons including evaluation of intercomparisons between sUAS-based measurements and ground-based measurements as well as statistical comparisons between measurements captured by

Figure 4: Aerial photo of some of the participants on the public outreach day located at Moffett Field near Alamosa, CO on July 14, 2018. Calibration and validation experiments were also conducted on this day.

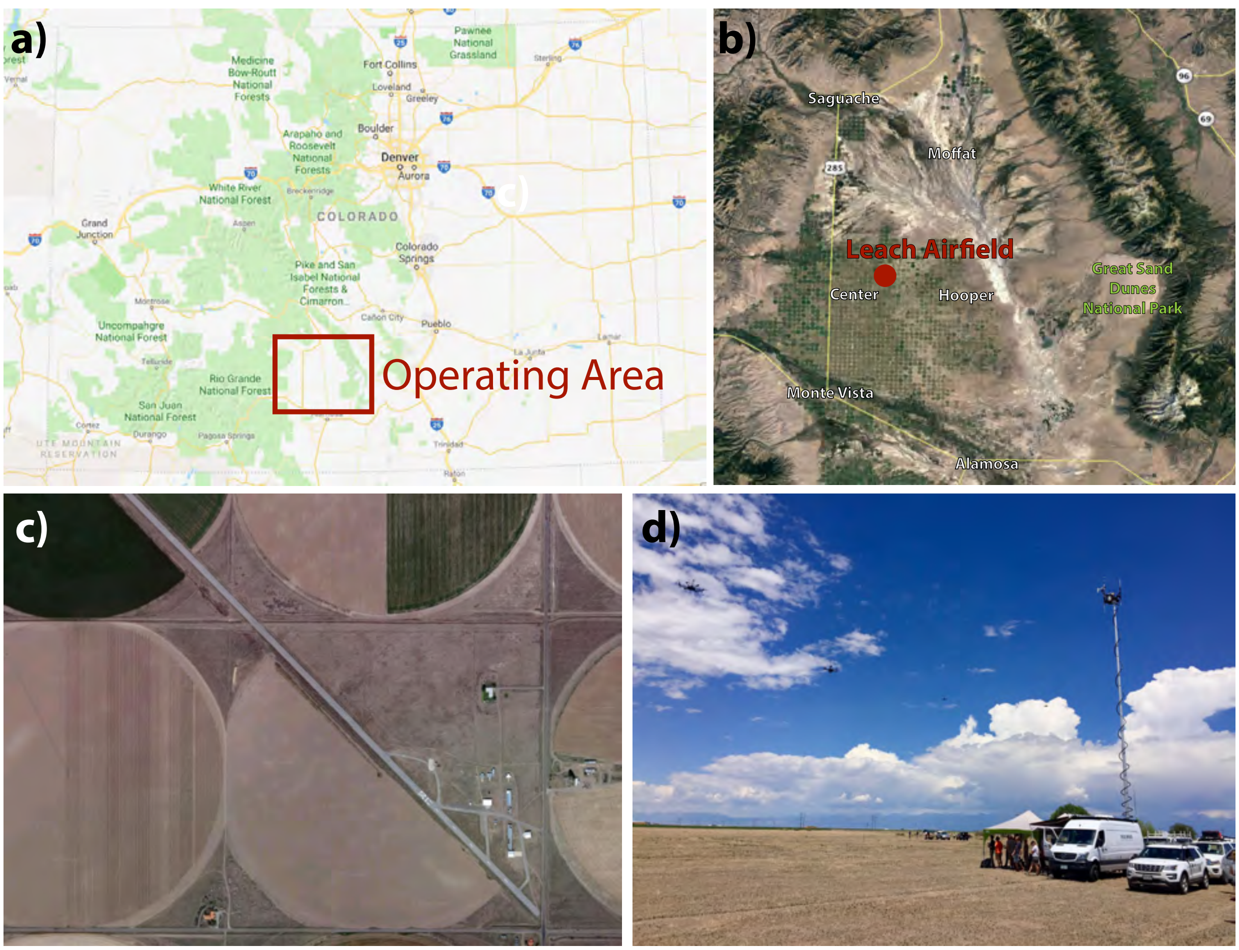


Figure 5: Maps illustrating the location of flight operations during LAPSE-RATE. (**a**) Operating area. (**b**) Leach Airfield. (**c**) The largest map (right) shows a satellite image of the area around Leach Airfield [Images courtesy of Google Maps]. (**d**) MURC facility.

different aircraft systems. In addition, this discusses these intercomparison results in detail and reflects on the potential causes of the observed differences, best practices based on the results of this intercomparison study, and additional perspectives on the future direction of sUAS-based atmospheric measurement. More detail will be provided in a comprehensive paper set for publication later this summer.[**?**]

2.1.1 Time response of measurement systems

The comparison provided in Figure 6, provides an opportunity to assess the impact of the different sensor configurations on the time response of the temperature and humidity measurements. Note that this assessment does not take into account all possible influencing factors and is an attempt to quantify some of the effects of time response qualitatively observed when examining the data. In addition, we aim to assess the system as a whole (sensors and their arrangement on the aircraft) with the expectation that this integrated response will be quite different from manufacturer stated response.

In Figure 6c,d the higher the *amd*, the greater the mean difference between the ascent and descent measured profiles shown in Figure 6a,b, respectively. Assuming a stationary profile of T or RH, this would reflect slower response of the measurement systems. To account for non-stationarity of the true profile, these results are presented in Figure 6e,f compensated for the variability during the measurement using the *mad* in time reported by the MURC (Mobile UAS Research Collaboratory). This step implies the assumption that the variability observed at the height of the MURC platform is representative for the variability of the vertical column that has been profiled. It should also be noted that this analysis will not highlight systems with response times on the order of the ascent/descent times of the flight, as these systems will report the same values for both ascent and descent. Similarly, a very uniform profile, without any significant vertical gradients, is also likely to be reflected in a very good agreement between the ascent and descent profiles.

Generally, no clear trends were evident, with identical systems presenting different values. However, it does appear that the fine-bead thermistor-based temperature measurements (e.g. _xq, _xq2, and _pt100), which have faster manufacturer-stated response times, slightly outperformed the integrated-circuit-based temperature sensors (e.g. _BME280, _AQT400, _SHT31, _ds). In addition, systems with no aspiration demonstrated greater symptoms of sensor lag than those incorporating similar sensors without some form of aspiration. For example, the system that produced the largest $amd(T)$ and $amd(RH)$ values had the sensors mounted underneath the body of the multirotor airframe and out of the rotorwash. The systems that provided values of $amd(T) - mad(T_M)$ and $amd(RH) - mad(RH_M)$ near zero were predominantly those with some sort of aspiration of the sensors. In addition, it was observed that sUAS-sensor combinations with high negative $amd(T) - mad(T_M)$ and $amd(RH) - mad(RH_M)$ values did not seem to resolve temporal and spatial variations well (see the very straight relative humidity profiles in Figure 6(b).)

2.1.2 Trends and broader discussion

In summary, the sUAS systems show broad agreement with the truth values, particularly for temperature. There were no clear differences between fixed-wing and mutirotor platforms in

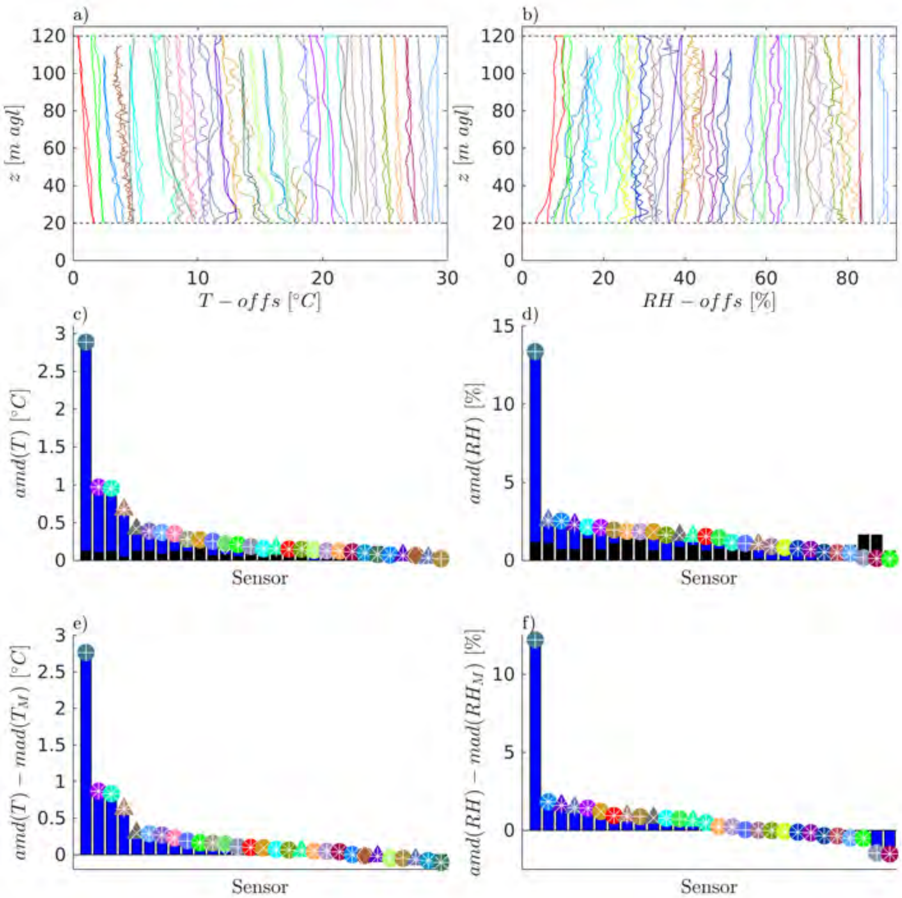


Figure 6: Comparison of temperature and relative humidity profiles taken during ascent and descent. Profile data between 20 m and 120 m AGL for temperature and relative humidity are shown in (a) and (b), respectively. The profile data is shifted by an artificial temperature/humidity offset to increase the visibility of the profiles. The second row shows the absolute-mean-deviation between ascent and descent data (blue) and the corresponding mean-absolute-deviation of the MURC data for the corresponding times (black) for temperature (c) and relative humidity (d). Markers are used to identify the different platform-sensor configurations as in [**?**]. The last row shows the difference between the profile's absolute-mean-deviation and the MURC mean-absolute-deviation for temperature (e) and relative humidity (f).

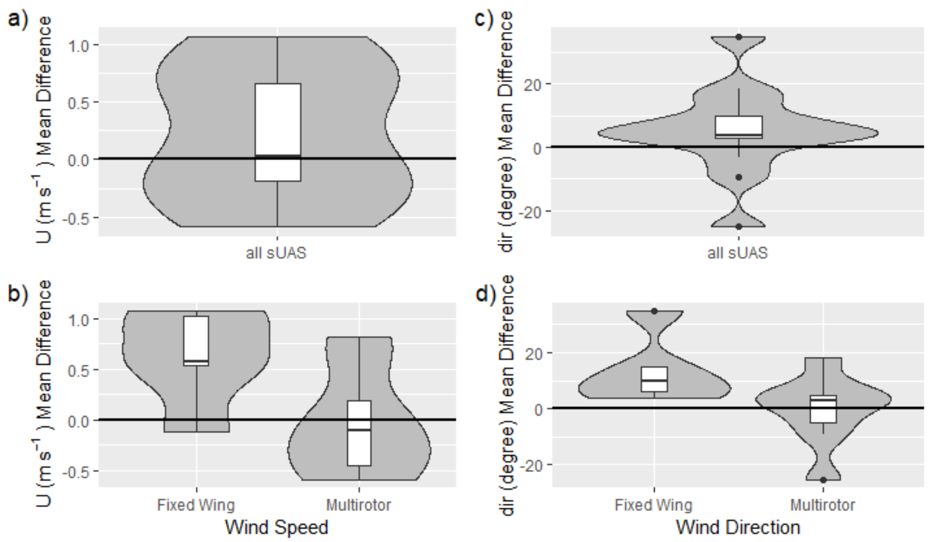


Figure 7: Comparison of difference (MURC-sUAS) in wind speed and wind direction measurement in relation to the MURC measurements - represented with the black line at 0. Averages of parameter measurement differences over each platform's MURC intercomparison loiter period are shown for all sUAS and then compared by platform. Wilcoxon rank-sum tests were performed, no significant differences were reported although near-significant differences were observed: $p(U) = 0.09$; $p(dir) = 0.07$.

the measurement of P, T and RH, although wind measurements made by hovering multirotor aircraft were found to be in closer agreement to the measured wind speed and direction than those made by orbiting fixed-wing platforms. Variability between the wind measured by nearly identical different aircraft also suggests that individual aircraft calibrations may play a considerable role in the accuracy of these measurements.

The time response and overall accuracy of T and RH measurements were dependent on the aspiration and solar shielding of the sensors, which is consistent with previous work [**?**]. Some differences were also observed between systems using integrated-circuit-based temperature sensors and those utilizing fine-bead thermistor sensors. Non-aspirated and unshielded sensors generally deviated from the MURC reference value to a greater degree, and unaspirated sensors demonstrated symptoms of measurement lag, particularly for T. Bias was generally observed between the sUAS and MURC T, RH and P measurements. The sUAS on average higher than the ground observations in T, and P measurements, with the sUAS measurement values of RH generally lower than the truth values. Further, the RH disagreement exceeds the stated uncertainty for the sensors used. Hence, some caution is advised when interpreting reported accuracy of RH sensors when deployed on sUAS. It should be mentioned that these biases are consistent with the sUAS being slightly lower in altitude than the ground sensors.