



## Considerations for temperature sensor placement on rotary-wing unmanned aircraft systems

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**Abstract.** With their recent surge in commercial accessibility, rotary-wing unmanned aircraft systems (rwUAS) are proving to be a viable method of atmospheric sensing and sampling while improving upon the shortcomings of traditional methods. To maximize the potential for these platforms to provide reliable observations, it is imperative to have an understanding of their strengths and limitations under varying environmental conditions. This study focuses on the quality of measurements relative to sensor locations on board rwUAS. Typically, thermistors require aspiration and proper siting free of heat sources to make representative measurements of the atmosphere. In an effort to characterize ideal locations for sensor placement, a series of experiments were conducted in the homogeneous environment of an indoor chamber with a pedestal-mounted rwUAS. A suite of thermistors along with a wind probe were mounted inside of a solar shield, which was affixed to a linear actuator arm. The actuator arm was configured such that the sensors within the solar shield would travel underneath the platform into and out of the propeller wash. The actuator arm was displaced horizontally underneath the platform while the motors were throttled to 50 percent, yielding a time series of temperature and wind speed which could be compared to temperatures being collected in the ambient environment. Results indicate that temperatures may be biased on the order of 0.5–1.0°C and vary appreciably without aspiration, sensors placed close to the tips of the rotors may experience biases due to frictional and compressional heating as a result of turbulent fluctuations, and sensors in proximity to motors may experience biases approaching 1°C. From these trials, it has been determined that sensor placement underneath a propeller on an rwUAS a distance of one quarter the length of the propeller from the tip is most likely to be minimally impacted from influences of turbulence and motor, compressional, and frictional heating while still maintaining adequate airflow. When opting to use rotor wash as a means for sensor aspiration, the user must be cognizant of these potential sources of platform-induced heating when determining sensor location.



## 1 Introduction

The planetary boundary layer (PBL) is the lowest layer of the troposphere which exchanges energy with the Earth's surface (Stull, 1988), and acquiring atmospheric measurements in this region has proven to be challenging (Hardesty and Hoff, 2012). In the past, in-situ PBL measurements have been taken primarily with instrumented towers (e.g. Charba, 1974; Shapiro, 1984; Poulos et al., 2002), which are immobile and limited in vertical extent, and balloons (e.g. Holden et al., 2000; Poulos et al., 2002; Seidel et al., 2010), which are costly and have limited vertical resolution. Furthermore, remote sensors such as wind profilers, scanning Doppler lidars, and radiometers are capable of continuously observing a fixed location (e.g. Grund et al., 2001; Poulos et al., 2002; Banta et al., 2015; Bonin et al., 2015; Lundquist et al., 2017), but rely on numerous assumptions about the atmosphere and have trouble resolving measurements close to the surface.

For several years now, small unmanned aircraft systems (sUAS), specifically fixed-wing UAS (fwUAS), have provided a unique ability to observe previously unattainable regions of the PBL both in space and time (Lothon et al., 2014; Wildmann et al., 2014; Båserud et al., 2016; de Boer et al., 2016; Bailey et al., 2017). Instrumentation on fwUAS has followed closely in the footsteps of operational manned research aircraft, and the body of literature regarding thermodynamic measurements has made these platforms a valuable resource (Saïd et al., 2005; Gioli et al., 2006; Reuder et al., 2012; van den Kroonenberg et al., 2012; Bonin et al., 2013). However, fwUAS come with several notable disadvantages, namely their inability to sample a vertical column at a fixed horizontal position, risks when operating close to the ground, and the need for a suitable surface for landing and possibly takeoff. Currently, rotary-wing UAS (rwUAS) are being realized as a viable supplement to fwUAS thanks to their autonomous vertical takeoff/landing capabilities and advancements in autopilot technology (Broisy et al., 2017; Voemel et al., 2018). The international network of operational radiosonde systems serve as the current standard for vertical profiling, and their observations are widely assimilated into numerical weather prediction. However, their limited spatio-temporal resolution is incapable of properly resolving PBL processes (National Research Council, 2009). As such, integration of rwUAS with observational networks and research efforts has the potential to vastly improve our understanding of processes occurring in the lowest regions of the atmosphere at unprecedented scales. It is therefore imperative for data collected by these platforms to achieve the highest possible degree of environmental representativeness as rwUAS become more commercially accessible.

As one application, rotary-wing UAS can be used to measure the same thermodynamic and kinematic properties as radiosondes: pressure, temperature, relative humidity, and horizontal wind speed and direction (Neumann and Bartholmai, 2015; Broisy et al., 2017). However, when making measurements, the platform itself can influence these observations. There are a number of factors that can affect any single measurement and each observation must be carefully designed and examined to ensure that it is as free as possible from external influence. In this study we focus on the effects of sensor placement on temperature observations.

To ensure that a thermometer, such as a thermistor, produces accurate measurements, it is critical that the sensor be well aspirated and properly mixed with the ambient environment (Tanner et al., 1996; Richardson et al., 1999; Hubbard et al., 2004). Moreover, sensor self-heating can lead to significant measurement bias in some thermistors if not properly accounted for. Thermistors use a temperature sensitive resistor to measure temperature. By knowing the input voltage and measuring how



it changes across the thermistor, the resistance of the temperature sensitive resistor can be determined, and thus the temperature. If current is run constantly through the resistor, heat is generated. Such a sensor must be properly aspirated or the resultant heat can modify the ambient environment, thereby influencing the measurement itself.

Observations of temperature from tower-mounted thermistors typically utilize solar-shielded chambers with fans to mechanically aspirate the sensors to improve data quality (Brock et al., 1995; McPherson et al., 2007). However, when considering the integration of sensors into a rwUAS, utilizing a fan poses a dilemma. Although a fan could ensure proper aspiration, this would draw power and add weight to the platform and potentially significantly decrease flight duration. Therefore, an alternative solution to this problem could be to aspirate the sensors with the air currents produced by the rotating propellers, or rotor wash. However, due to the complex flow around a rwUAS in flight, the location on the rwUAS providing the best aspiration is not obvious. Too little airflow and the sensor could self heat or not adequately sample the ambient atmosphere. Too much airflow and compressional heating of the air stream becomes an issue (Rodert, 1941). Furthermore, dissipation of heat from the rotary motor can also alter the measured air. Flow in proximity to the propeller tips is also associated with the highest values of turbulent intensity and temperature fluctuations (Swean and Schetz, 1979). After initial experiments involving rwUAS for research efforts, it was determined that a more in-depth examination of sensor location was needed to ensure data quality.

## 2 Equipment

With the questions surrounding temperature sensor placement on a rwUAS, an experiment was created to objectively determine the optimal location for quality temperature measurements, which is the primary focus of this study. To accomplish the task, the placement of the sensors relative to the rwUAS is discussed below.

### 2.1 Rotary-wing aircraft

The University of Oklahoma's custom-built CopterSonde rwUAS facilitates a symmetrical carbon fiber hashtag design with a diameter of 65 cm and is driven by eight brushless electric motors and 25 cm diameter propellers. The maximum payload mass amounts to 1 kg with a total all-up weight of about 7 kg. The maximum flight time is about 20 minutes. The CopterSonde has a top flight speed of  $25 \text{ m s}^{-1}$  and thus can be flown safely in winds up to a maximum horizontal speed of  $20 \text{ m s}^{-1}$ . The CopterSonde is equipped with a Pixhawk autopilot (3D Robotics, Inc.) which relies on an on-board inertial measurement unit (IMU) for attitude estimation. A barometric pressure sensor is used to control the altitude of the rwUAS. It also carries a post-processing kinematic differential GPS unit which gives centimeter positioning accuracy in space. External sensor data are sent to the Pixhawk via the I<sup>2</sup>C protocol, which are processed in parallel to the flight controls. This setup allows for a single consolidated data stream sent to the ground station over wireless radio using the Mavlink protocol. The operative distance of the communication system is around 5 km, capable of 15 km with upgraded antennas.



## 2.2 InterMet temperature sensors

To make temperature observations on the CopterSonde platform, International Met Systems (iMet) temperature sensors were used. These bead thermistors offer a response time of 2 seconds in still air (approximately 1 second with  $5 \text{ m s}^{-1}$  aspiration) over a range of  $-95$  to  $+50^\circ\text{C}$ , with an accuracy of  $\pm 0.3^\circ\text{C}$  and a resolution of  $0.01^\circ\text{C}$ . They are similar to the kind of sensors used on many standard radiosondes and is ideal for use on a rwUAS. The sensors were calibrated using an Oklahoma Climatological Survey aspirated chamber located outside the National Weather Center in Norman, Oklahoma. Offsets for each sensor were determined over a period of several hours of a typical late afternoon in early spring, with temperatures comparable to room temperature. Thus, these offsets provide an implicit self-heating correction while aspirated.

The bead thermistors are one component of a bigger iMet system specifically designed for UAV applications: the iMet-XF UAV. This system uses a main board to which different types of thermodynamical sensors can be interfaced. It samples each connected sensor successively, including on-board GPS and pressure sensors, and provides these data in packets through serial communication. Acquiring and storing the data can be achieved in a variety of ways: using a pair of radios to stream data to a ground station, or the unit can be connected to a computer for direct data streaming using the provided iMet software.

On the CopterSonde, the iMet thermistors were utilized in conjunction with a custom data acquisition unit. These data were then streamed and recorded on a ground station computer using a radio frequency link. The iMet temperature sensors are equipped with an integrated circuit board that converts the analog data stream into an I<sup>2</sup>C format. To streamline data input to the CopterSonde's flight controller (Pixhawk), a custom circuit board was developed that is capable of accepting and synchronizing 8 separate I<sup>2</sup>C sensor inputs and converting them to a single output data stream. A module was programmed for the Pixhawk to sample each sensor successively at a given rate, log their data on-board, and stream live data to the ground station.

## 2.3 NSSL Mobile Mesonet

To provide a comparison with the temperature data recorded using the iMet thermistors, a modified version of the National Severe Storms Laboratory (NSSL) Mobile Mesonet (MM) rack was used. The equipment rack, normally mounted to the roof of a vehicle, is capable of temperature, pressure, wind speed and direction, relative humidity, and solar radiation observations. For the tests presented here, the equipment rack was mounted to a cart. This allowed the rack to be placed in close proximity to the CopterSonde during measurements.

To measure temperature, two stainless steel probes from Campbell Scientific known as the 109 were used. One was mounted inside an aspirated radiation shield and one was mounted to the CopterSonde. The 109 has less than  $0.03^\circ\text{C}$  linearization error over the range of  $-50$  to  $+70^\circ\text{C}$ , with a  $\pm 0.2^\circ\text{C}$  tolerance between  $0$  and  $70^\circ\text{C}$ . The thermistor is contained within a stainless steel housing, meant for use in damp conditions such as soil moisture measurements, and as such has a response time of 30 s with  $5 \text{ m s}^{-1}$  airflow. The sensors used for this study had been recently calibrated by the Oklahoma Climate Survey group and shown to be within specifications.



## 2.4 Oklahoma Mesonet hot wire anemometer

In addition to measuring temperature, it is also relevant to measure the flow rate past the temperature sensor location. This allows one to assess the extent to which the probes are in a "well mixed" environment and provides insight to the conditions that are being experienced by the sensors themselves. A Thermo Systems Inc. (TSI) hot-wire anemometer was used to gather  
5 precise velocity measurements as close as possible to the temperature sensor location.

## 2.5 Linear actuator arm

The overall goal of the experiment was to find locations on a rwUAS where temperature readings are most representative of the environment. With this in mind, data collected at multiple locations on the rwUAS needed to be examined to determine where the sensors experience influence or bias relative to ambient air. To achieve this, the thermistors were placed on a linear  
10 actuator arm capable of moving the sensors horizontally directly underneath two of the motor mounts, as depicted in Figure 1. The initial starting position at point A was 6.5 cm outside of one propeller, and the the sensor position was systematically stepped 0.24 cm per increment with a dwelling time of two seconds per increment across the width of the CopterSonde towards point B. This motion of the arm was controlled by the same procedure on the ground station communicating with the hot wire  
15 anemometer, which then recorded arm position, wind speeds, and computer timestamps at each step. The ending location was 12.5 cm outside the opposite side of the rwUAS, and took approximately 35 minutes to complete the process. Two of the iMet temperature sensors were attached to the arm, as was a 109 temperature sensor from the NSSL MM rack. Combining these three different files (NSSL logs for the NSSL probes, Pixhawk logs for the temperature sensors, and the computer logs for the arm and the anemometer) with their common timestamps therefore allowed for synchronized analysis of the separate data streams.

## 20 3 Thermistor self-heating experiment

Prior to analysis of the sensor placement temperature profiles detailed in later sections, a baseline depiction of the iMet thermistor self-heating is required. A simple experiment consisting of three thermistors and a ducted fan was conducted to isolate the effects of aspiration. The fan was located at the base of a solar shield duct, which was bent at a right angle with sensors inserted through holes along the top. With the fan switched on, this configuration induces airflow to enter from the horizontal,  
25 pass across the sensors, and exhaust downwards through the fan.

The sensors were initially powered on and began collecting data while the fan was off. After holding this position for approximately six minutes, the fan was powered on, pulling air across the sensors at  $6 \text{ m s}^{-1}$ . The fan was then alternately switched on and off for periods of two to three minutes each, for a total of three cycles.

A time series of the iMet temperature responses are displayed in Figure 2, along with green and red dashed lines denoting the  
30 times the fan was switched on and off, respectively. The data presented are the raw, uncalibrated output at 10 Hz. Although they are uncalibrated, the sensors closely track with one another while the fan is on and are only linearly offset. It is immediately



apparent that the sensors react to airflow through the solar shield, as temperatures repeatedly drop over 1°C in under 20 seconds. Prior to the first time the fan was switched on, the setup had been sitting idly for several minutes. However, following the fan being switched off, the sensors indicated temperature increases. For these periods, the observed heating was likely due to a combination of both sensor-self heating and the fan motor radiating heat upwards towards the sensors. This hypothesis is supported by iMet sensor 2 being in closest proximity to and directly above the fan while also heating the most rapidly. Furthermore, the other two sensors were higher up and displaced horizontally due to the geometry of the duct, and they showed slower heating rates while the fan was off. The key evidence for sensor self-heating is that the sensors return to their same respective temperature levels each time the fan was on, regardless of how they behaved while the fan was off. Therefore, this supports the requirement of sensor aspiration to properly measure the environmental temperature.

## 4 Anechoic chamber experiments

### 4.1 Setup

The University of Oklahoma Radar Innovations Laboratory has a large anechoic chamber used for calibration and testing of radar components and other electronic equipment. This chamber however also provides a reasonably homogeneous environment for testing when it is necessary to isolate the effects of various sensor influences on a rwUAS without solar radiation concerns or changes to the ambient environment. To offset the vertical variations in temperature that could exist in such a room, a common carpet fan was aimed at 45° from horizontal and turned on to maximum airflow about 15 minutes before the experiment to mix the environment. The CopterSonde was mounted on a large pedestal near the center of the room with a bracket that accommodated the vehicle and a linear actuator arm as previously mentioned (Figure 3a).

To simulate the wind flow of the aircraft in flight, the iMet and NSSL thermistors and Mesonet wind probe were positioned inside of a 3D-printed plastic solar shield (Figure 3b, c). Due to the spatial constraints of the setup, the NSSL probe was mounted vertically and underneath the iMet and wind sensors in an effort to measure the same air stream. Furthermore, to avoid bias in temperatures measured from the NSSL probe beneath the hot wire anemometer, the wind probe was removed for the final round of testing.

For each experiment, the actuator arm was mounted so that the sensors would pass directly underneath the motor mounts as the linear actuator arm moved horizontally. Relative positions of each sensor to the rwUAS are detailed in Figure 1.

To provide a reference background temperature of the ambient environment, a second 109 sensor on the NSSL MM rack was mounted inside the aspirated U-tube radiation shield (not depicted). A second iMet thermistor was also suspended 50 cm below the CopterSonde, allowing for reasonable (but turbulent) aspiration, as determined from previous trials not included in this study. The additional measurements provided by the suspended iMet thermistor and the NSSL MM 109 probe inside the radiation shield, were used to identify the "ambient" environment. For the purposes of these tests, the autopilot inputs to the motor throttle were bypassed, allowing for direct manipulation of throttle input using an external device.



## 4.2 Procedure

Upon receiving power, the iMet and NSSL thermistors began logging data. For the first trial, the motor position began at point A (6.5 cm horizontally from the tip of the nearest propeller, figure 1), and the battery was connected with throttle at zero, allowing the sensors to record un aspirated for 8 minutes. After this period, the CopterSonde was throttled up to approximately 55 percent maximum power to simulate the airflow typical during slow ascent. Although not directly under the propellers, airflow across the sensors was  $2 \text{ m s}^{-1}$ , sufficient enough for aspiration. This position was sustained for 2 minutes before powering the motors off again. The sensors then remained in quiescent conditions for 2.5 minutes before throttling to 55 percent again. After giving the sensors 40 seconds to aspirate, the linear actuator was then incrementally moved towards point B by 0.24 centimeters, holding each position for 2 seconds. In total, it moved approximately 71.1 cm, which was outside of the rotor wash on the "B" side of the configuration. This experiment took a total of approximately 35 minutes to complete.

To control for the effects of potential heat advection from the hot-wire anemometer, the same test was conducted after removing the wind probe from the solar shield. During this second trial, however, the initial start-stop-start of the motors was not performed. The CopterSonde and sensors were powered on for 2.7 minutes, then the throttle was increased to 55 percent for 35 seconds before incrementing the linear actuator arm's position.

## 5 Results and discussion

### 5.1 Experiment 1 - wind probe in tube

Temperature and velocity are plotted versus relative time as the sensors moved along the linear actuator arm during the first experiment in Figure 4. To account for the longer response function of the NSSL probes and to make more appropriate comparisons, a moving boxcar average of the iMet temperatures was applied to 10 seconds before each analysis point; wind speeds displayed are the raw output. Furthermore, the hot-wire anemometer had not been calibrated prior to this experiment, and thus values displayed may not be absolute; however, confidence in relative precision is still high.

In figure 4, the background temperature is shown by the NSSL 109 probe (dotted black) and the iMet sensor (solid black). The CopterSonde temperatures are shown by the iMet sensor (solid blue), while the reference temperature of the NSSL 109 is shown in solid red. The figure also shows the air velocity at the CopterSonde sensor location (solid orange), showing clear signs of passing through the rotor wash of the propellers as the linear actuator moves from one side of the rwUAS to the other. This is indicated by peaks in the velocity as the hot-wire approached  $17 \text{ m s}^{-1}$  flow rates, before decreasing to near zero directly underneath the motor. A second minimum was encountered between the two propellers, before a similar pattern was observed while the sensors passed under the second propeller. A gradual increase of  $0.5^\circ\text{C}$  was observed by both background temperature sensors over the course of the 35 minute experiment, likely attributable to the mechanical mixing of the chamber environment.

This velocity pattern demonstrates that when considering sensor location for adequate airflow, directly under the motors or between the two propellers is not a viable option. While the first conclusion might be obvious, a relative minima in the flow



velocity was not expected between the propellers. In addition to the velocity structure, Figure 4 shows that differences do exist between the various sensors, and that a steady increase in temperature on all sensors was measured over the duration of the experiment.

A closer look at the first 16 minutes of this analysis relative to the background temperature (Figure 5) reveals evidence of the self-heating phenomenon. For over 8 minutes, the probes in the solar shield recorded 0.2–0.4°C above the relatively constant background, with variations owing to the presence of the hot-wire anemometer. During this period, the motors of the CopterSonde were not on, thus no aspiration to the sensor existed. Once the motors initially throttled up (green dashed line), temperatures dropped to within 0.1°C of the reference, and remained in this range until the motors were shut off again 2 minutes later. Immediately after throttling down, temperature began rising again, by 0.5°C in under 3 minutes. Finally, when throttled back up again at the 13 minute mark, temperatures returned to anomalies of 0.1°C in under 30 seconds.

Although influences from the anemometer are likely inherent during this initial period, the overall response of the sensors to aspiration matches results from the experiment discussed in section 3. It can therefore be concluded that rotor wash is capable of mitigating the decoupling of sensors from the ambient environment, so long as the sensors are free from other external sources of heating which will be discussed below.

After the motors turned on at the 13-minute mark, the actuator arm began translating underneath the aircraft. Due to the complexity of the flow field underneath propellers rotating at several thousand revolutions per minute, it is reasonable to believe that small nuances in temperature depicted can be caused by limits in sensor accuracy and sampling rates in turbulent flow. There are, however, several identifiable trends that are attributable to artificial sources such as motor heat and sensor decoupling.

At minute 15.5, the probes intercepted a warm stream of air likely owing to turbulent fluctuations and compressional heating on the tip of the propeller spreading down and outward. A similar observation is made on the other end of the CopterSonde at minute 28. At minute 16, the sensors moved under the propellers and out of the warm air stream from the tips, allowing temperatures to stabilize within 0.1°C of the reference temperature. This pattern is consistently observed underneath the four peaks in wind speed, representing: exterior propeller 1, interior propeller 1, interior propeller 2, and exterior propeller 2, in order.

As the actuator arm moved the sensors underneath the CopterSonde's motor mounts from minutes 18–19.5 and 25–26.5, temperatures rapidly rose 0.5–0.8°C over the course of 1 minute. Since temperatures began rising with wind speeds well above levels at the beginning of the experiment (2–4 m s<sup>-1</sup>), the source of this increase was not necessarily solely due to self heating. Instead, their proximity to the motors leads to the conclusion that the sensors were intercepting hot air streaming off the motors.

Finally, the sensors mounted on the arm sampled the space in between the interior propeller tips at minutes 21.5–23. Wind speeds dropped to marginal levels, similar to those at the initial position of the sensors. Subsequently, a small (0.1°C) temperature rise is noted in both the iMet and NSSL sensors. Because the aspiration rates were similar to those at the beginning of this experiment, the primary driver of this temperature rise was likely a warm air stream originating from the hot wire anemometer. In order to remove this effect, a second analogous experiment was performed by removing the wind probe.



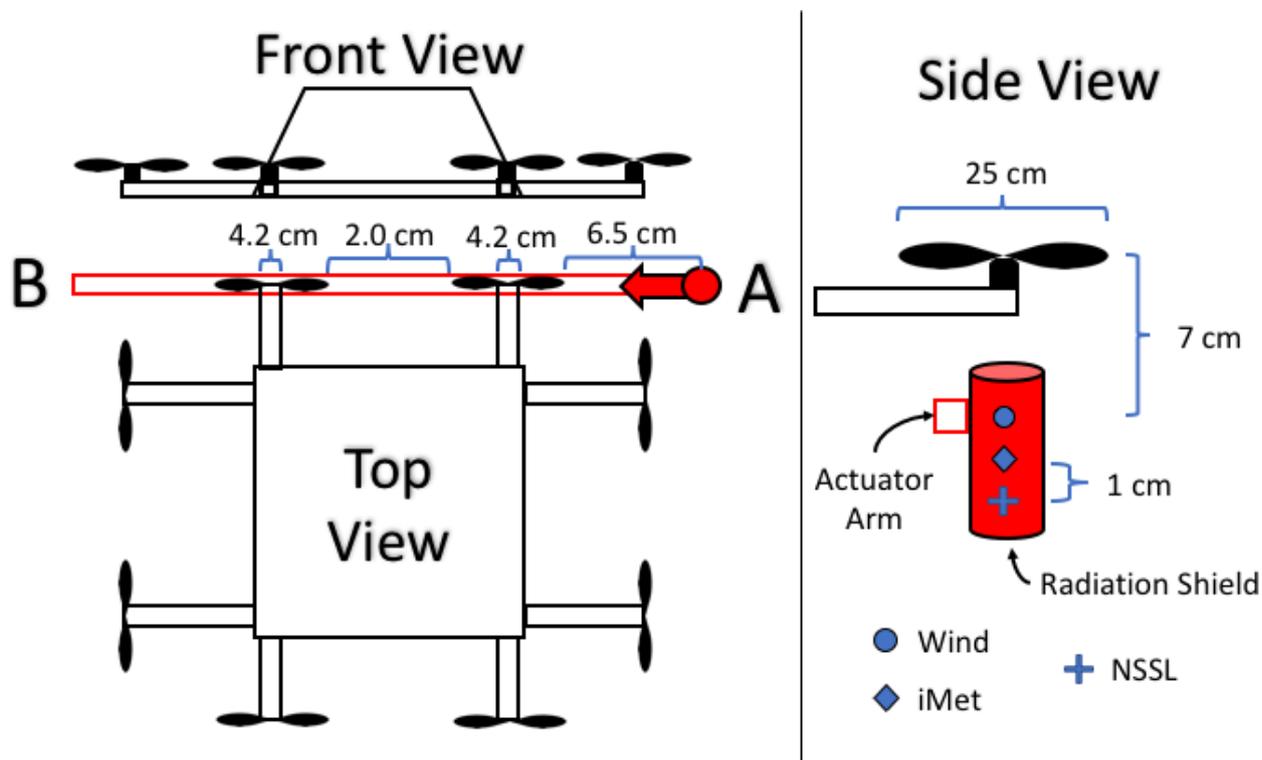
## 5.2 Experiment 2 - no wind probe

- In the repeated experiment, sensors were allowed to remain unaspirated for about 2.75 minutes before throttling up and moving the linear actuator arm, similar to experiment 1 except without the initial aspiration test. Although the wind probe was removed, the actuator arm increments were identical, so wind speeds from experiment 1 are plotted in Figure 6 for reference. In general, the temperature pattern was largely similar to the results from experiment 1: symmetrical about the center of the two propellers, increases in temperature on the outside tips, and large increases underneath the motor mounts. However, the small rise in temperature in between both propellers was no longer observed, and the overall increase in temperature underneath the motor mounts was 0.1-0.2 °C less than in experiment 1. Therefore, the hot-wire anemometer was likely biasing temperature readings in this region of relatively stagnant flow.
- Finally, the CopterSonde's battery rapidly approached critical as the motors were shut off at minute 18.5, so temperature trends after this mark should not be strongly considered.

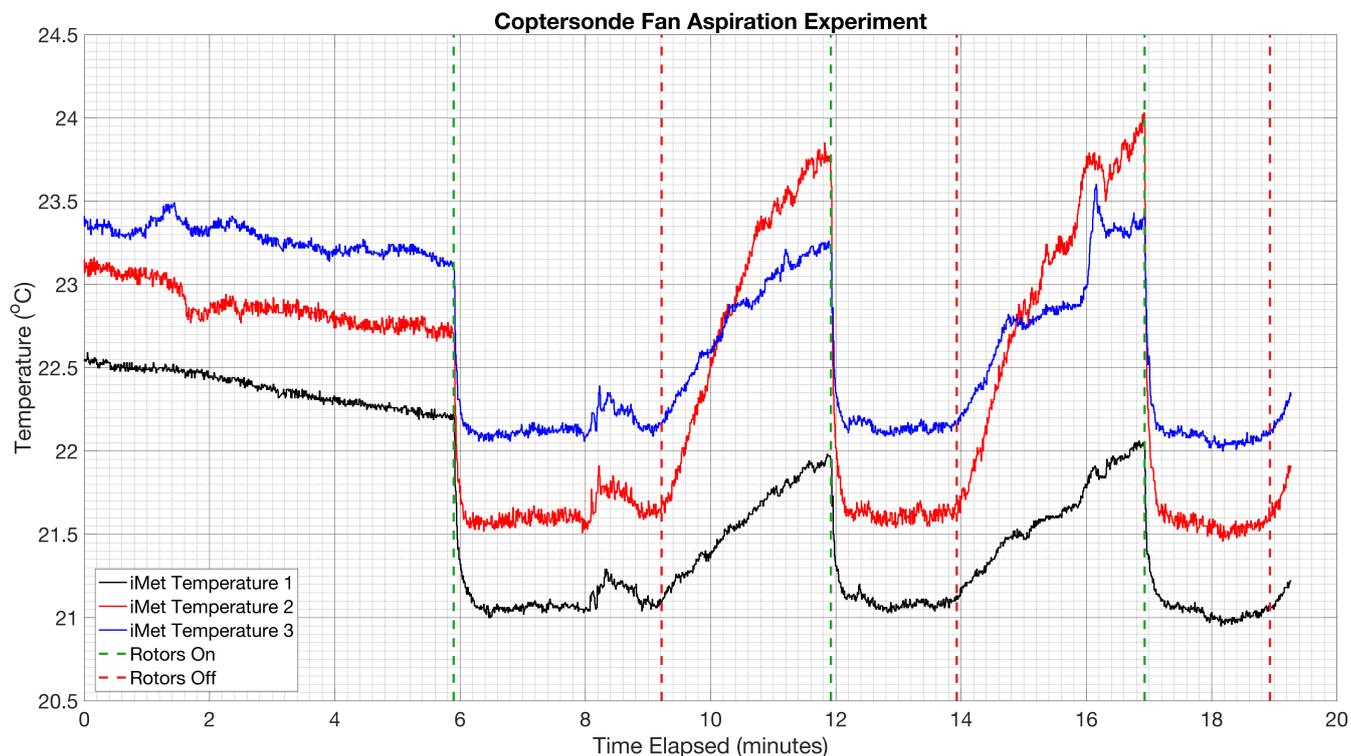
## 6 Conclusions

- One must take special consideration regarding sensor placement when attempting to measure environmental temperature using a rotary-wing UAS because these platforms are prone to modifying their own environments. In order to determine sensor locations free of systematic biases, multiple experiments were conducted in a relatively homogeneous chamber, where sensors were sequentially displaced underneath the rotor wash from a mounted rwUAS. Results from the two experiments presented, as well as other trials not described, provide useful guidelines with regards to sensor placement. Several sources of temperature bias exist, including (but not limited to) those observed in this study: sensor self-heating, compressional heating and turbulent fluctuations from the propeller-modified air streams, and heating from the motors.
- Given these results, out of the locations tested the optimal position for measuring environmental temperatures while hovering or ascending with a rotary-wing UAS is in a solar shield about 5–10 cm below the propeller and one third the length of the propeller from the tip. This location provides ample aspiration while avoiding the warm air streams from the motor and propeller tips. Other locations above or below the UAS run the risk of encountering stagnation in flow, which can exaggerate the effects of self-heating and generally decouple the sensor from the environment. Furthermore, proximity to external heat sources such as batteries or the rotary motors are also capable of introducing artificially warmed air streams. By following these general guidelines, it is of the authors' opinions that rwUAS are capable of obtaining trustworthy atmospheric measurements across a variety of applications.

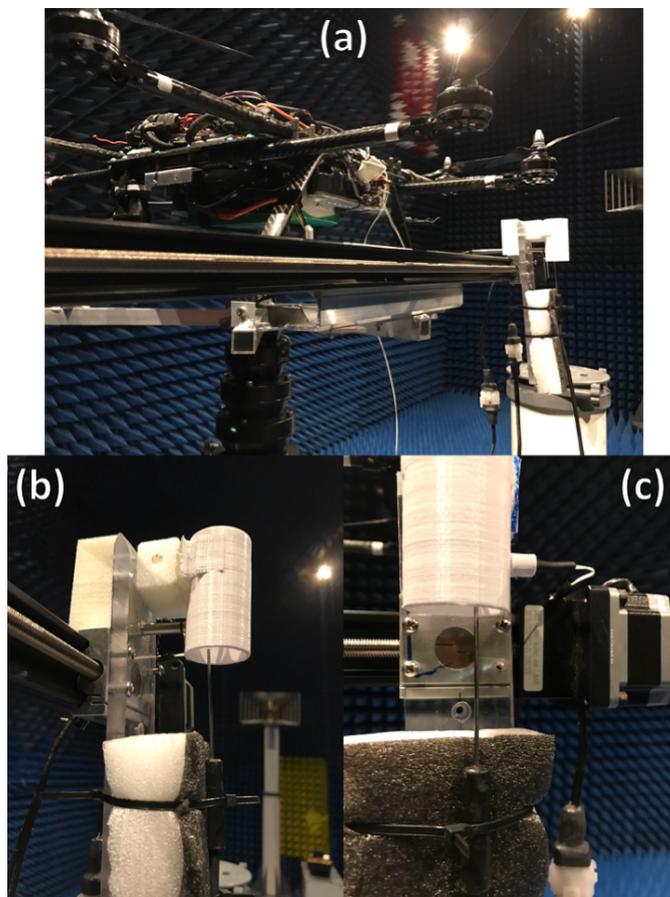
*Code and data availability.* Data and code are available upon request to the corresponding author.



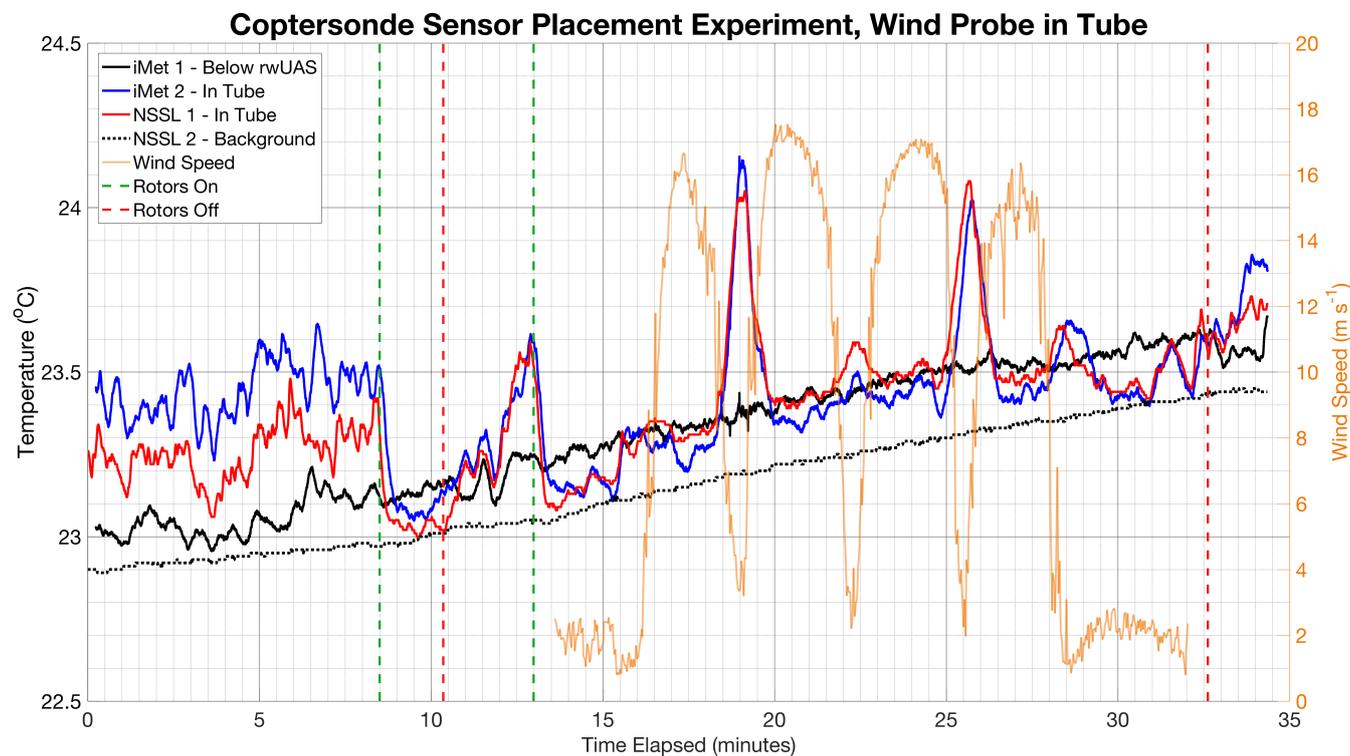
**Figure 1.** Setup schematic and dimensions of the rwUAS used in this study (drawing not to scale). In front and top view, the linear actuator arm is represented by the red rectangle outline, and the sensor package as red circle. The arm was displaced from point A to point B, directly underneath the motor mounts and one pair of propellers as seen in the top-down and side views.



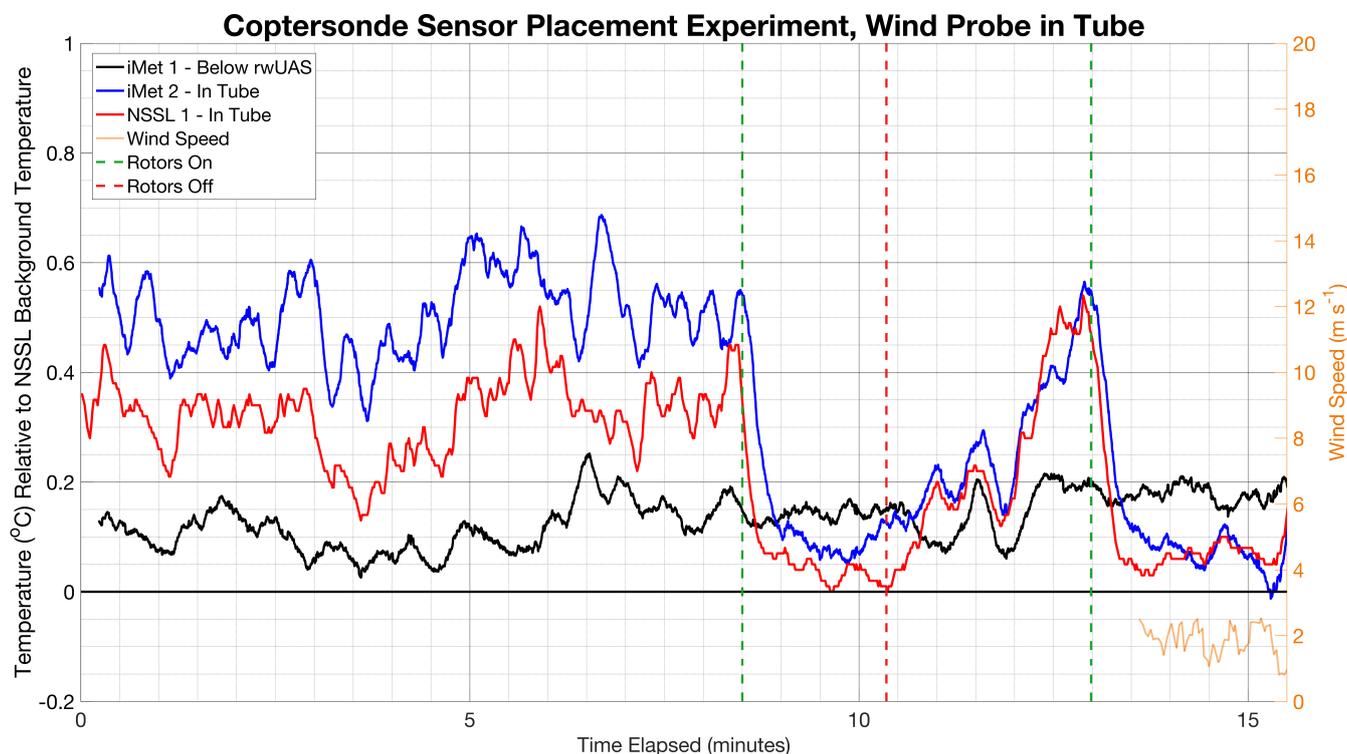
**Figure 2.** Sensor aspiration experiment identifying sensor self-heating. After the fan is switched on initially (green dashed line), temperatures drop over 1°C in response to coupling with the ambient environment. Each time the fan turns off (red dashed lines), temperatures rise as a result of self-heating and the fan radiating heat. Temperatures return to the same levels each time the fan is turned on, indicating proper sampling of the environment when aspirated.



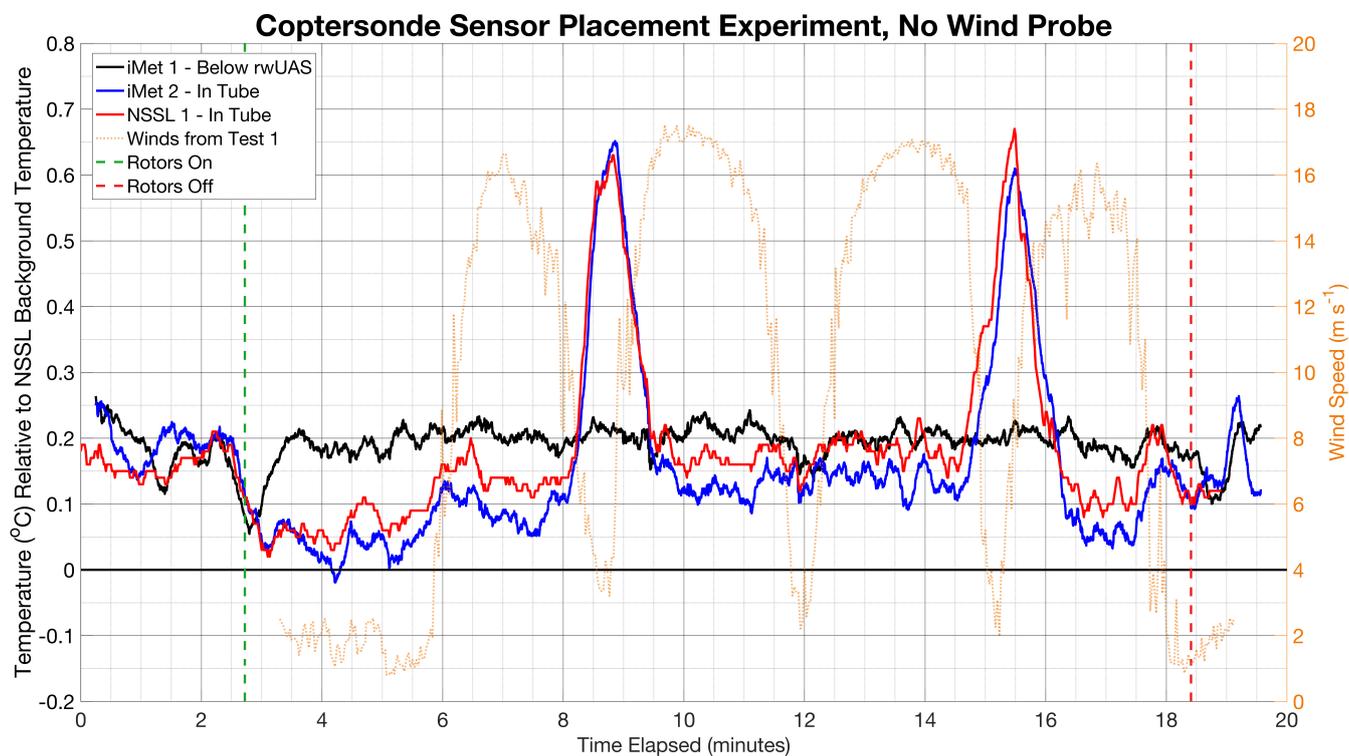
**Figure 3.** a: Position of linear actuator arm underneath rWUAS on mounting pedestal. Arm was aligned such that sensors passed directly underneath the motor mounts so as to make the system essentially two-dimensional. b, c: Close-up view of a. Location of iMet thermistor, Mesonet wind probe, and NSSL thermistor inside solar shield.



**Figure 4.** Experiment 1 - temperature and wind speed vs. relative time, entire time series. Temperature response to aspiration noticeable between minutes 8.3–10.3. Compressional heating off tip of propeller at minute 15.5 just as wind speed picks up. Rise in temperature underneath motor mount at minute 19. Small rise in temperature between two propellers at minute 22.3 due to hot wire anemometer in stagnant air. Same pattern reflected for second half due to symmetry of setup.



**Figure 5.** Temperatures ( $^{\circ}\text{C}$ ) relative to NSSL background temperature at the beginning of experiment 1. This perspective emphasizes sensor self-heating (in addition to bias from the hot wire anemometer) as the propellers are throttled on and off (green and red vertical dashed lines, respectively). Furthermore, the initial difference between NSSL sensors can be attributed to the presence of the anemometer in the radiation shield. While wind speeds were not recorded during this time, it is reasonable to extrapolate the  $2.5 \text{ m s}^{-1}$  reading backwards from minute 13.6 since the sensor position was fixed.



**Figure 6.** Experiment 2 - temperature and wind speed vs. relative time. Winds from experiment 1 included for reference. Results are similar to experiment 1, but the lack of small temperature rises in between the propellers indicates that the hot wire anemometer was modifying air streams to an extent. Therefore, this is a more characteristic depiction of an rwUAS in flight.



*Competing interests.* The authors declare that they have no conflicts of interest.

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