# Using Thermocouple, Thermistor, and Digital Sensors to Characterize the Thermal Wake Below Ascending Weather Balloons

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**In this paper we present additional results from our on-going research effort to characterize the thermal wake that trails below ascending latex weather balloons on flights into the stratosphere; a wake which interferes with the ability of temperature sensors in payload boxes hanging from the balloon (and hence enveloped by the wake) to correctly measure the ambient temperature of the atmosphere through which the balloon is ascending. A "wake boom" is used to measure temperature variations up to 1.5m horizontally from varying distance directly below the neck of the balloon. Results to date agree with the literature that especially above the tropopause the thermal wake is warmer than the ambient air during daytime ascents, due to solar radiation warming the balloon skin, but colder than ambient air during night-time ascents, due to adiabatic cooling of the gas inside the balloon (which also occurs in the daytime, but is smaller than the daytime warming effect). In particular, we report on thermal wake characterization using (Neulog) thermocouple sensors, as compared to (HOBO) thermistors and (Arduino-logged) DS18B20 digital temperature sensors. We also present additional results from X-shaped 2-dimensional wake booms or "X-Booms" which allow us to compare wake temperatures on the sun side versus the shade side of the balloon, looking for asymmetries in the horizontal temperature profile.**

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# I. Introduction

Ongoing work related to temperature measurements collected in the stratosphere continues to draw nearly the full attention of the ballooning team at St. Catherine University[1-4]. The process of characterizing the thermal wake below ascending latex weather balloons has proved to be non-trivial and the scope needed to be more narrowly focused from the proposed project laid out in last year's report[4]. We have worked with (Neulog) thermocouple sensors extensively in the past year. The use of these sensors once familiar to the user (they are surprisingly easy to incorrectly program), has been mostly positive. In addition, we have continued the use of DS18B20 temperature sensors logged via Arduino Mega microcontrollers with limited success.

# II. Review of the Thermal Wake

A thermal wake exists below an ascending balloon [1-6]. On a daytime flight the temperature of the air directly beneath the balloon will be warmer than the ambient air temperature due to solar radiation hitting the balloon. According to Brasefield, "…it may be concluded that, to altitudes of 100,000 ft, the air temperature below a balloon does not differ from the true ambient temperature by more than 1º C, so long as measurements are made at least 25ft below the balloon." [7] To be "in the thermal wake" we make temperature measurements within 20ft of the base of the balloon, near the top of the stack. In addition to the daytime phenomena, an opposite effect occurs during night flights, when the adiabatic gas temperature inside the balloon is lowered which then lowers the balloon skin temperature. [5] The cooled skin of the balloon cools the air beneath the balloon, affecting temperature measurements below the balloon. The effect in both the daytime and nighttime is stronger with a decrease in air pressure. For "Reynolds numbers smaller than $10^5$, the thickness of the heat exchange layer d will increase with decreasing pressure, where $d \approx \left(\sqrt{P}\right)^{-1}$, (where P = air pressure)."[5]

# III. Questions posed at the 5th annual AHAC conference and investigated July 2014-June 2015

A) Study of the thermal wake effect:
   - A.1.1 How do different temperature sensors add to the knowledge of the thermal wake effect?
   - A.1.2. What is the wake profile as a function of altitude for the daytime effect?
   - A.1.3. What is the wake profile as a function of altitude for the nighttime effect?

B) What can we learn from Arduino Microcontroller data?
   - B.1.1 What will having magnetometer data, coupled with GPS stamped data, allow us to measure in the near space environment?

# IV. Methods

All flights for 2014-2015 have used 1600-gram Hwoyee balloons using Helium as a lift gas.

Flights had a minimum of two types of temperature sensors on wake boom arm (carbon fiber tubing, white electrical tape wrapped cables with sensors all pointing upwards)– often times with one or two duplicated locations to cross check readings. A summary sensor list of used appears below: [8-11]

| Sensor Brand | HOBO TMC6-HD | Neulog NUL-234 | Dallas DS18B20 |
|---|---|---|---|
| Listed Temperature Range | -40 to 100 C | -200 to 2000 C | -55 to 125 C |
| Dimensions | 5.1 by 33 mm copper capped cylinder | 1.0 by 13 mm wrapped wires | 4mm by 4mm by 3mm half barrel |
| Sensor type | Thermistor | Thermocouple | Digital |

Table 1: Listing of sensors specifications and type used for wake measurements.

Since our summer 2014 report the one dimensional wake-boom experiment has flown on two daytime balloon missions and one nighttime mission.

In our paper from 2014 [4] we also discuss the unique capabilities of flying an X-boom. Figure 2 from Ref. 5 (reproduced below) suggests an asymmetry in the thermal wake. During a night flight the thermal wake is colder than the ambient air temperature (perhaps uniformly colder, as shown in the figure) but during a day flight the sun heats the sun-side of the balloon more than the anti-sun (AKA shadow) side, resulting in a thermal wake that is warmer on the sun-side and cooler on the anti-sun side, but still warmer than the ambient air temperature. This thermal asymmetry might be observable with a wake boom: when the boom is oriented parallel to the sun/anti-sun direction the wake should be warmer on the sun side and less warm (but still warmer than the ambient air temperature) on the anti-sun side; when the boom is oriented perpendicular to the sun/anti-sun direction the thermal wake should be warmer than the ambient air temperature but symmetrical (possibly uniformly warmer, as suggested by the figure).

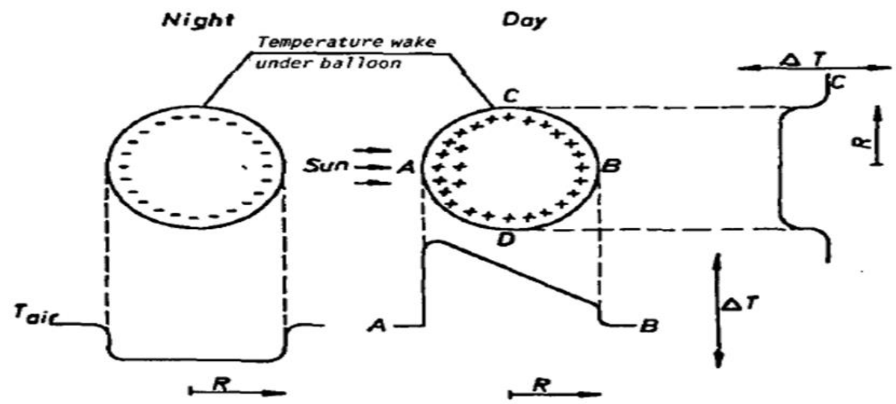


Figure 1: Symmetrical (Asymmetrical) temperature of balloons and thermal wakes during Night (Day) ascents. Figure reproduced from Reference 5.

St. Catherine University has built an Arduino logged X-Boom to study the daytime asymmetry created by a sun side and anti-sun side to a thermal wake. See photo below.

Figure1. The St. Catherine University X-Boom set to fly.

Figure 2. Launching the X-Boom.

For numbering continuity with prior papers Reference 1, 2 and 3, these flights will be called 3N, 11D, 12D and 3X, where “D” refers to a daytime flight and “N” refers to a nighttime flight. “X” refers to an X-boom (daytime) flight.

3N: 7-18-2014—A one dimensional boom was flown from Claremont, MN, to an altitude of 32,884 meters. The flight landed just North of Bath, MN after burst at 0:33a.m. The wake boom had five Neulog sensors located at 0, 8, 20, 30 and 40cm from the middle of the boom, directly under the balloon. In addition, eleven HOBO sensors were flown at locations of 0, 3, 5, 8, 12, 17, 30, 50, 60, 75 and 130cm. Eight DS18B20 sensors were flown at 0, 5, 10, 20, 30, 40, 60 and 130 cm. The Arduino microcontroller was housed in a lower payload with a cable extending up to the carbon fiber wake boom.

11D: 8-15-2014 –A one dimensional boom was flown from St. Peter, MN, to an altitude of 29,133 meters. The flight landed South of Waldorf, MN after balloon burst at 12:21p.m. The wake boom had five Neulog sensors located at 0, 8, 20, 30 and 40cm measured out from the center of wake. In addition, eleven HOBO sensors were flown at locations of 0, 3, 5, 8, 12, 17, 30, 50, 60, 75 and 130cm. Eight DS18B20 sensors were flown at 0, 5, 10, 20, 30, 40, 60 and 130 cm. The Arduino microcontroller was housed in a lower payload with a cable extending up to the carbon fiber wake boom.

12D: 11-02-2014 – A one dimensional boom was flown from Pemberton, MN, to an altitude of 27, 420 meters. The payload landed West of West Concord MN after balloon burst at 1:25 p.m. The wake boom had five Neulog sensors located at 0, 8, 20, 30, 40 cm from the center. In addition, eleven HOBO sensors were flown at locations of 0, 3, 5, 8, 12, 17, 30, 50, 60, 75 and 130cm. Eight DS18B20 sensors were flown at 0, 5, 10, 20, 30, 40, 60 and 130 cm. The Arduino microcontroller was housed in a lower payload with a cable extending up to the carbon fiber wake boom.

3X: 3-22-2015 – A two--dimensional X-Boom was flown from Madelia, MN, to an altitude of 25,360 meters. The payload landed East of Hayfield MN after balloon burst at 12:28. One of the boom arms had five Neulog sensors located at 0, 8, 20, 30 and 40cm. Forty four Arduino--logged DS18B20 sensors were divided into four sets of eleven sensors on each arm. In addition, this flight had a magnetometer on the end of one of the wake arms.

## V. Results

The first of the sensor comparisons were conducted on a night flight 3N.

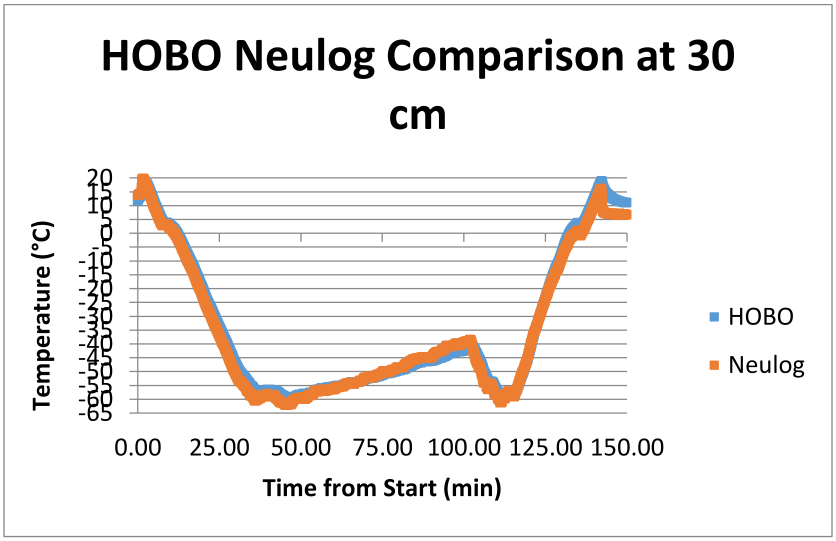


Figure 3. Sensor comparison at common location.

The Neulog sensors were compared to the HOBO sensors near burst altitude. The Neulog sensors tended to run warmer on the outer areas of the wake arm.

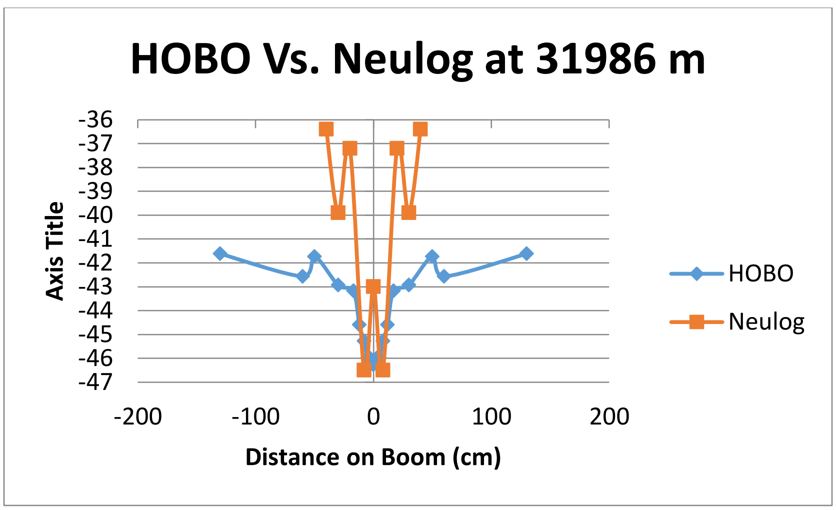


Figure 4. Sensor comparison near burst for night flight.

Continued daytime investigation using Neulog sensors was conducted, the data collected from the thermocouple sensor (Neulog) was compared to the thermistor sensor (HOBO)

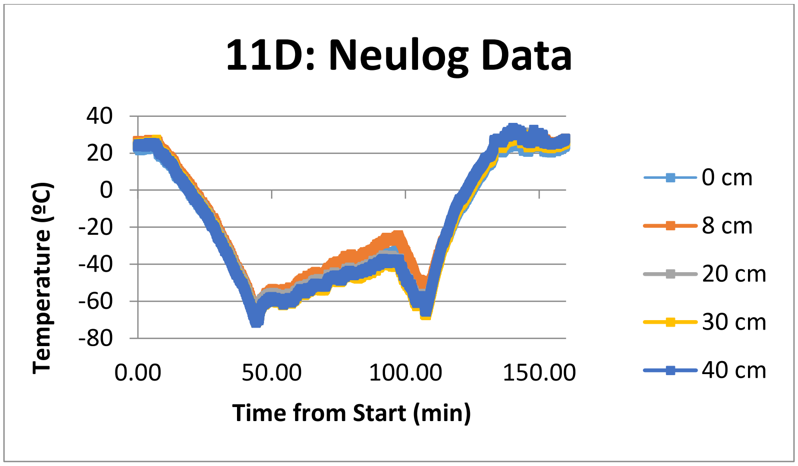


Figure 3. A full flight profile for the first run of daytime data from Neulog data collected in 2014.

Time slices of the data were plotted as was done in reference 4.

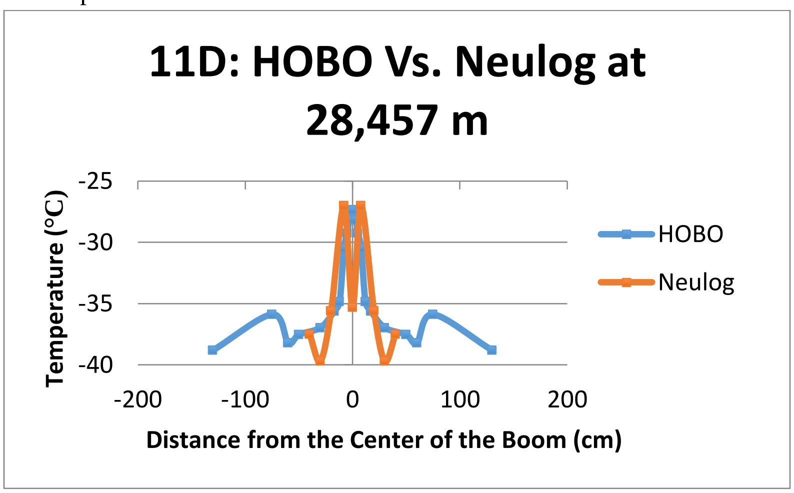


Figure 4. HOBO versus Neulog sensor comparison near burst. Symmetry is assumed.

We also compared the Arduino and HOBO data sensors, both located at 40cm.

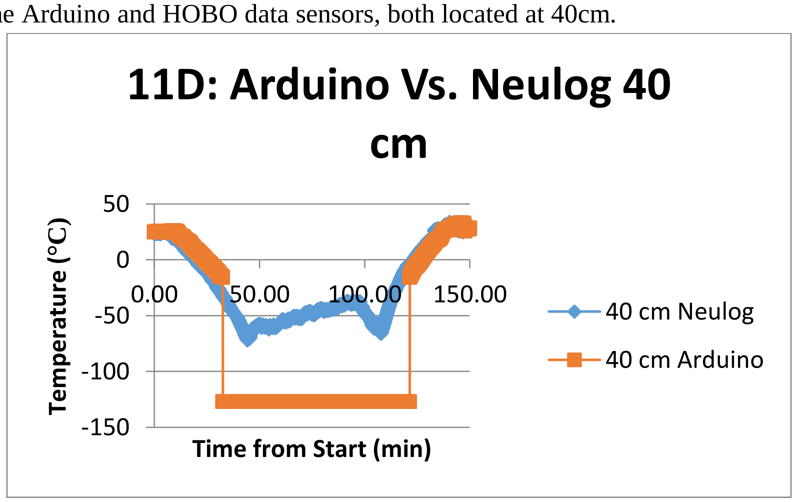


Figure 5. Sensor comparison, Unfortunately on this flight the Arduino data cut out at -16 Celsius on ascent and but came back on in at -18 Celsius on descent, suggesting a thermally and pressure induced failure.

After this flight we conducted a freezer test to examine sensors and check whether the Arduino microcontroller was getting too cold and therefore failing to log the sensors. Additional thermal insulation was used in payload box along with lithium batteries.

A Neulog and HOBO sensor comparison was done for the entire flight. Some variance was observed in the tropopause as well as in the stratosphere. Post burst the variance was very minimal.

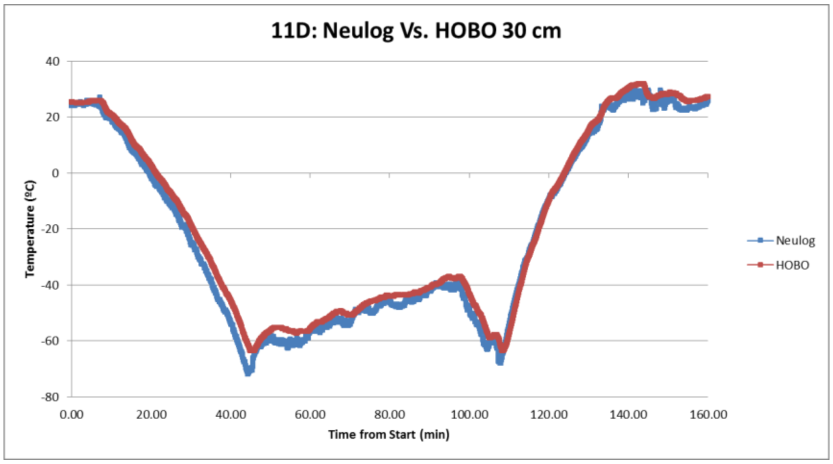


Figure 6. Neulog versus HOBO temperature sensor comparison.

Figure 6 Flight 12 D was a follow up flight to try and compare different sensors. Figures 7 and 8 look at Neulog and HOBO time slices about 10 minutes prior to burst, at altitude

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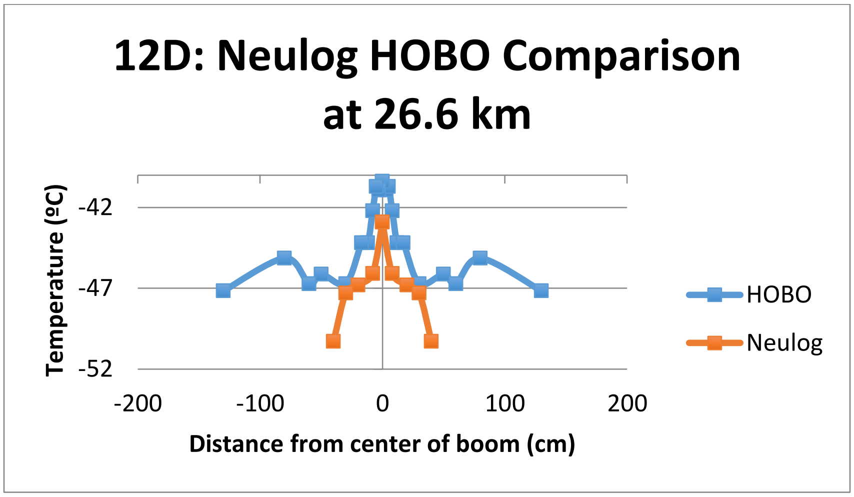


Figure 7. Flight data about 6 minutes before burst looking at sensor differences between Neulog and HOBO sensors. Symmetry is assumed – sensors were actually only on one side of the center.

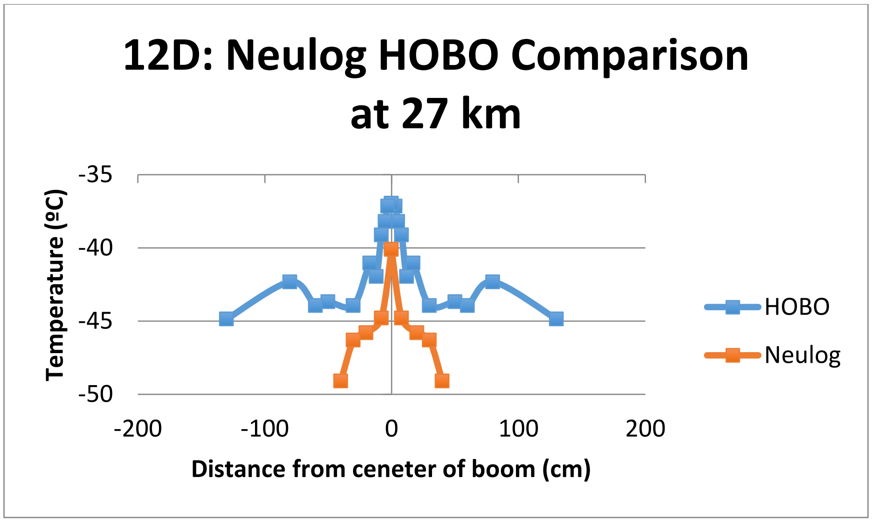


Figure 8. Neulog and HOBO flight data comparison just prior to burst for flight 12D

Neulog sensors tended to run much cooler on flight 12D, as compared to flight 11D; about 2 degrees Celsius cooler, on average. Given that no changes were made between the two flights, this change is hard to understand.

The X-Boom flight had the similar dropout of the Dallas temperature sensors on ascent, then recovery on descent, so that issue remains unresolved. Thermocouple data was similar to that logged in other flights.

Magnetometer data was collected at the end of one of the wake arms to determine direction. A circular histogram was used to plot the directional data using Mathematica.

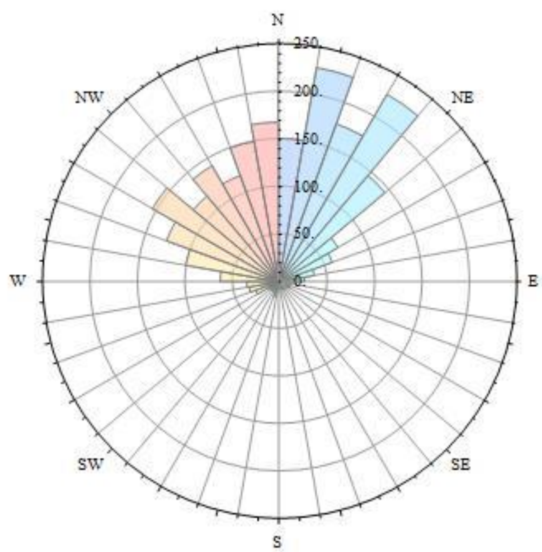


Figure 9. Magnetometer data from the 3X flight – circular histogram indicates frequency of direction in every 10 degrees. This data suggest the payload didn't rotate very much during the flight, a conclusion not borne out by examination of the on-board video. We continue to work on understanding the source of this discrepancy.

## VI. Questions for summer 2015 consideration

How do different temperature sensors and calibration adjustments add to the knowledge of the thermal wake effect?

A.1.1 What can we learn about offsets created at very low pressures occurring later in the flight?

A.1.2 Correlate thermocouple, thermistor and Dallas temperature sensors and create ranges for sensor data.

A.1.3 Correlate wake temperature as a function of ascent rate and find a correlation with the Reynolds number and the heat transfer rate.

What can be learned from wake experiments to study the upper tropospheric environment and stratospheric environment?

B.1.1 Better understand what "typical" profiles for wake sensors for daytime and nighttime flights show in these regions of the atmosphere.

B.1.2 Prepare for flights in the changing environment of the 2017 solar eclipse.

## VII. Conclusion

Box proximity issues are somewhat mitigated by placing the wake boom arm separate from the payload box. This is more difficult with HOBO data loggers and Neulog sensors as the temperature probes have fixed lengths. A distance of at least 10cm has been maintained on flights 12D as well as 3X.

We have appreciated having multiple sensors on our wake arms. We are longing for the day when we can reduce payload weight and go with a single lightweight reliable system. We are closer to this goal than last year but not as far along as projected in Reference 4.

Testing just temperature or pressure by itself in not sufficient in itself as the Dallas temperature sensors have been run down with low pressure (fractions of atms) and low temperatures (-80 C in our Biochemistry freezer). The key is to have tests that run both temp as well as pressure at the same time. Construction of a lab-quality freezer that can pull a partial vacuum is critical for sensor testing as well as calibration.

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