Continued Exploration of the Thermal Wake Below Ascending High-Altitude Balloons

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We present an update on our on-going investigation of the thermal wake that trails below ascending high-altitude balloons. We use a 1-dimensional array of temperature sensors called a "wake boom" to measure air temperatures up to 1.5m horizontally from points directly below the balloon. Our results concur with reports that the thermal wake is warmer than the surrounding air during daytime ascents due to solar radiation hitting the balloon skin, but colder than ambient air during night-time ascents due to adiabatic cooling of the gas in the balloon . In particular, we will report results from using Arduino microcontrollers to log data from DS18B20 digital temperature sensors. We will also give preliminary results from an X-shaped wake boom (AKA "X –Boom"), which allows us to study whether the hot side of the balloon (AKA the "sun side") results in an asymmetry in the thermal wake horizontal temperature profile.

I. Introduction

The process of studying temperature changes in the stratosphere using temperature sensors was started in a paper presented at the 3rd Annual Academic Balloon Conference[1]. Early work showed that a thermal wake could be measured using off-the-shelf HOBO temperature sensors. Temperature sensors were shown to be quite sensitive to placement on or around the payload. This work was developed further in Ref. 2 presented by St. Catherine University students at the 4th Annual Academic Balloon Conference. A series of research questions were also set forth as topics to study. Some of the questions were addressed in Ref. 2, but many underwent further development[3]. Here we present results to questions that were addressed since the last paper.

In addition to addressing research questions from last summer, we have proceeded to investigate the use of Arduino Uno microcontrollers for data logging. HOBO data loggers have a major limitation. Temperature sensors with a limited lifetime that tend to break or malfunction at a higher rate the more often they are used. In addition, the HOBO data loggers themselves are somewhat cost prohibitive, especially when one chooses to fly upwards of 10 temperature sensors, and they come with a limited selection of cable lengths. Arduino Uno microcontrollers are less expensive than HOBO data loggers and DS18B20 digital temperature sensors are significantly cheaper than HOBO air/water/soil temperature sensors, and DS18B20 sensors may be custom-cabled. Arduino Uno microcontrollers,

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with a real time clock, also have the capability to log GPS data and can be paired with accelerometers, magnetometers, and pressure sensors. This host of programmable, extremely lightweight components is a big draw for us as we move forward in our investigation.

Given the cost-effectiveness of utilizing the DS18B20 temperature sensors, as compared to HOBO air/water/soil temperature sensors,[4] we looked to further the investigation set forth in Ref. 2. As outlined in Ref. 5, temperature asymmetry in the wake below an ascending balloon is theoretically predicted, but only during daytime ascents. The sun side of the balloon is predicted to be warmer than the anti- sun side of the balloon, creating a temperature gradient from the sun side to the anti-sun side of the wake. In order to measure this asymmetry, we developed an "X -boom" – four wake boom arms each 90 degrees to each other – fitted with eight DS18B20 sensors on each arm. The orientation of the X-boom arm with respect to the sun is documented with a video camera on a lower payload.

II. The Thermal Wake

A thermal wake exists below an ascending balloon.[1-3,5] 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 true ambient temperature by more than 1º C, so long as measurements are made at least 25 ft below the balloon."[7] To be "in the wake" we make temperature measurements within 20 ft of the base of the balloon, near the top of the stack. The length of the wake is not as clearly defined and it is apparently presumed to be even larger in extent.[5,6] In addition to the daytime phenomena, an opposite effect has been shown to occur during night flights, when the adiabatic gas temperature inside the balloon is lowered which then lowers the balloon skin temperature.[5] The cool skin temperature of the balloon cools the air beneath the balloon, affecting temperature measurements below the balloon. The effect in both the daytime and nighttime is said to be 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 $d \approx (\sqrt{P})^{-1}$, (P = air pressure)."[5]

III. Questions posed at the 4th annual AHAC conference and investigated July 2013 – June 2014

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

B) How does sensor shading and sensor placement (geometry) affect the reading?

B.1.1 Does placement of the sensors horizontally versus vertically alter the readings? That is to say, how many sensors are needed on a boom to define the spatial extent of the wake? A more-detailed study of the temperature profile as a function of distance for future wake booms may be of interest to compare to the theoretical model outlined in Ref 5.

IV. Methods

Note: All flights using Hwoyee balloons used 1600-gram balloons.

Since our summer 2013 report[2] the 1-D wake-boom experiment has been flown on 3 daytime balloon missions and 3 nighttime missions. We report on one of the daytime flights for this paper and two of the nighttime missions. See photo below.

Figure 1. The mixed HOBO and Arduino data logging boom being prepped by St. Kate's students.

For numbering continuity with prior Ref. 1 and 2, these flights will be called 1N, 9D, and 2N, where "D" refers to a daytime flight and "N" refers to a nighttime flight. Flights of the new X-boom built to study temperature asymmetries is labeled "X" and will only be flown for daytime ascents. The basic parameters of the 2013-2014 flights are as follows:

1N: 8-1-2013 – The boom was flown from New Ulm, MN, to an altitude of 32,231 meters under a Hwoyee balloon. The boom landed in Austin, MN after balloon burst at 00:42. The distance from the center of the boom to the base of the balloon was 326 cm. There were 11 white-painted HOBO sensors on the boom which were located at 0 cm, 5.3 cm, 9.7 cm, 20.1 cm, 30.2 cm, 40.1 cm, 60.7 cm, 71 cm, 19 cm, 132.1 cm, and 170 cm from the center of the box. All temperature sensors were on one side of the boom and symmetry was assumed based on previous data.

9D: 10-26-2013 – The boom was flown from Norwood Young America, MN, to an altitude of 33,244 meters under a Hwoyee balloon. The boom landed near Burr Oak, IA, after balloon burst at 14:10. The distance from boom to balloon was 326cm. There were 10 HOBO sensors located at 6 cm, 20 cm, 40 cm, 50 cm, 60 cm, 70 cm, 80 cm, 90 cm, 110 cm, and 167 cm from the center of the boom. All of the temperature sensors were located on one side of the boom and symmetry was assumed.

2N: 5-22-2014 – This was the second flight using multiple logging apparatus – we made use of both HOBO data loggers as well as Arduino microcontrollers logging DS18B20 digital temperature. This iteration of the dual-sensor-type boom was flown from Waterville, MN, to an altitude of 28,420 meters under a Hwoyee balloon. The boom landed south of Blooming Prairie, MN, after balloon burst at 00:58. The distance from boom to balloon was 580.8 cm. The boom had 14 white-painted HOBO sensors. Twelve were located at 0 cm, 2.5 cm, 4.5 cm, 7.5, cm, 11.5 cm, 14 cm, 20 cm, 30 cm, 40 cm, 51 cm, 60 cm, and 130 cm from the center on the right side of the boom. The other two were located 25 cm and 130 cm from the center on the left side of the boom, among the Arduino sensors. There were also 8 Arduino-logged sensors on the boom as well. Six of them were located at 5 cm, 11 cm, 13.5 cm, 19.5 cm, 32.5 cm, and 40 cm from the center on the left of the boom. The other two were located at 15.5 cm and 25.5 cm from the center on the right side of the boom, among the HOBO sensors.

1X (AKA "GL74A"): The X-boom flew to 28,345 meters on April 12, 2014. A 3000-gram Kaymont balloon was used, so we were disappointed by this relatively-low burst altitude. We were hoping to reach over 33,000 meters based on previous experience with such balloons.

The “X-boom”

Figure 2 from Ref. 5 (reproduced below) suggests an interesting 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).

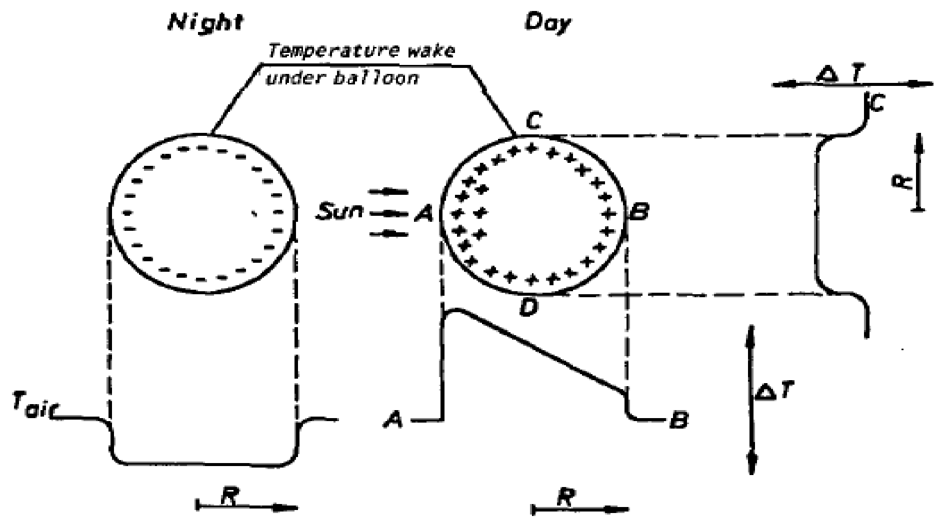


Figure 2. Symmetrical (Asymmetrical) temperature of balloons and thermal wakes during Night (Day) ascents. Figure reproduced from Ref. 5.

To measure asymmetry in the thermal wake, the following conditions need to be met as closely as possible. (A) The balloon should not rotate too quickly so that the sun-side has a chance to get and stay warmer than the anti-sun side. (B) The boom should not rotate too quickly with respect to the balloon lest the effect get smeared out as the temperature sensors swing through warmer and colder parts of wake. (C) The relative orientation of the boom, balloon, and sun needs to be monitored.

It turns out that condition (A) is naturally-occurring – if you observe rotation in up-looking views of high-altitude balloon in the stratosphere it is probably in the camera, not the balloon, though you may need to look very closely to notice this; this was actually a surprise to us, despite years of ballooning experience. Once we realized (as presented in Ref. 3) that balloons don’t rotate much at altitude, to accomplish condition (B) we decided to tie the boom ends directly to the neck of the balloon (more specifically, to a parachute basket attached to the neck of the balloon) to stop relative rotation between the balloon and the boom and, as an added bonus, to greatly reduce rotation of the boom itself with respect to the earth, vastly improving our look-out video footage. To accomplish (C) we placed an up-looking video camera in a payload box below the boom to watch the boom, balloon, and sun (or at least the sunny side vs. the shadow side of the balloon, from which we can determine the direction toward the sun).

Students in a U of MN freshman seminar constructed an “X-boom” to do this experiment which consisted of Arduino-logged digital temperature sensors spread over four boom arms held perpendicular to one another, as shown in the photo below. Arduino microcontrollers to log the over-40 temperature sensors were located in a central payload box which was white in color to minimize solar heating of the box since the boom was attached to the lid of the payload so the central sensors on each arm were very near the box.

We decided to use the X-shape to collect more data on a single flight and because the thermal asymmetry should show up nicely – when one pair of boom arms is oriented sun/anti-sun the other pair is naturally in the perpendicular direction. Figure 4 shows the X-boom just after launch on flight 1X.

Figure 3. **U of MN freshmen with their “X-boom” device prior to its inaugural flight.**

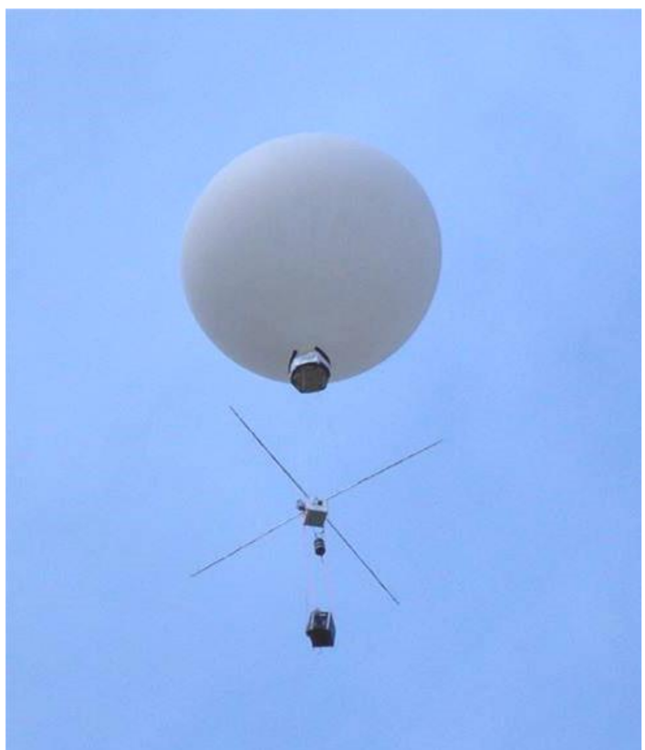


Figure 4. **The X-boom on flight 1X, tied to the parachute basket attached to the neck of a 3000-gram Kaymont weather balloon.**

Notice the parachute basket at the neck of the balloon (which, frankly, wasn’t ideal for the airflow we were trying to study) designed to keep the parachute from tangling with the multiple lines between the neck of the balloon and the X-boom below).

We called the arms A, B, C, and D, so A and C were across from one another, as were B and D, and we had temperature sensors at the following distanced from the center along each arm: 0 cm (i.e. a cluster of 4 sensors right at the middle, one from each arm), 5 cm, 10 cm, 25 cm, 45 cm, 65 cm, 90 cm, and 150 cm. We found that we could only log data from two arms on a single Arduino Uno, so one Uno was used for arms A and B (so we would get 2-D data) and a second Arduino for arms C and D. Additional "prime" temperature sensors were added at intermediate distances and logged by a third Uno. We filmed the boom and the balloon above it (and the sun location) with a Contour video camera looking up from the lowest payload.

V. Results

Continued daytime investigation using more HOBO sensors was conducted during flight 9D. The stratospheric portion of daytime ascent, where temperature separation of the sensors occurs, is shown in Fig. 5.

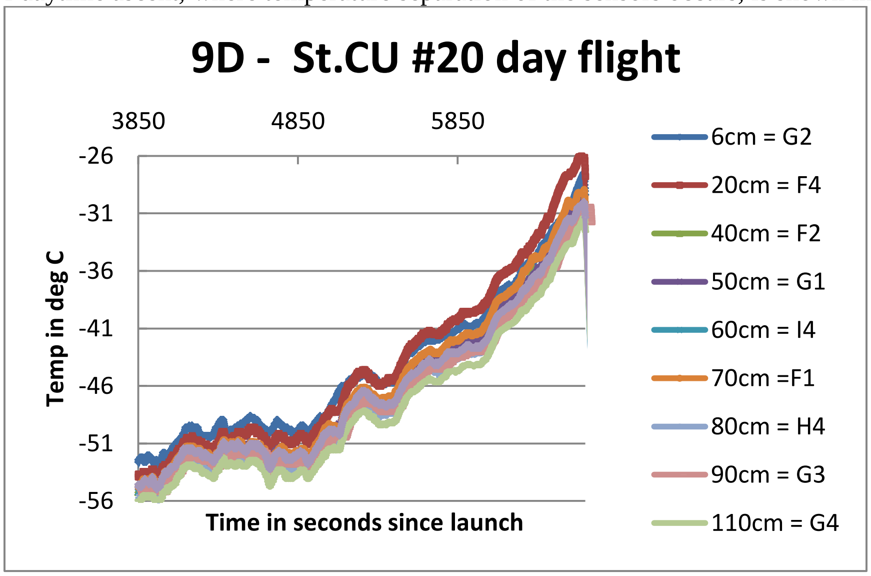


Figure 5. Graph showing HOBO temperature sensors values vs. time for a daytime flight conducted on 10-26-2013 – the data encompasses a latter portion of ascent plus a small portion of descent data.

Next we generated a graph of time slices (and their assumed mirror image) (Fig. 6) through the temperature data, showing the spatial profile of the daytime wake. Note the "warm" region (at least 4 degrees Celsius or warmer) that exists for sensors inside of 50 cm. This region is predicted in Ref. 5. The energy absorbed is assumed to be proportional to the balloon surface being hit by solar radiation. The increased number of temperature sensors we feel has captured the horizontal extent of the wake in much greater definition than in the past. However the larger number of sensors can also result in additional sensor offsets that could account for some of the temperature variation recorded. Interestingly enough, switching sensors and loggers and re-flying different configurations have all produced similar profiles.

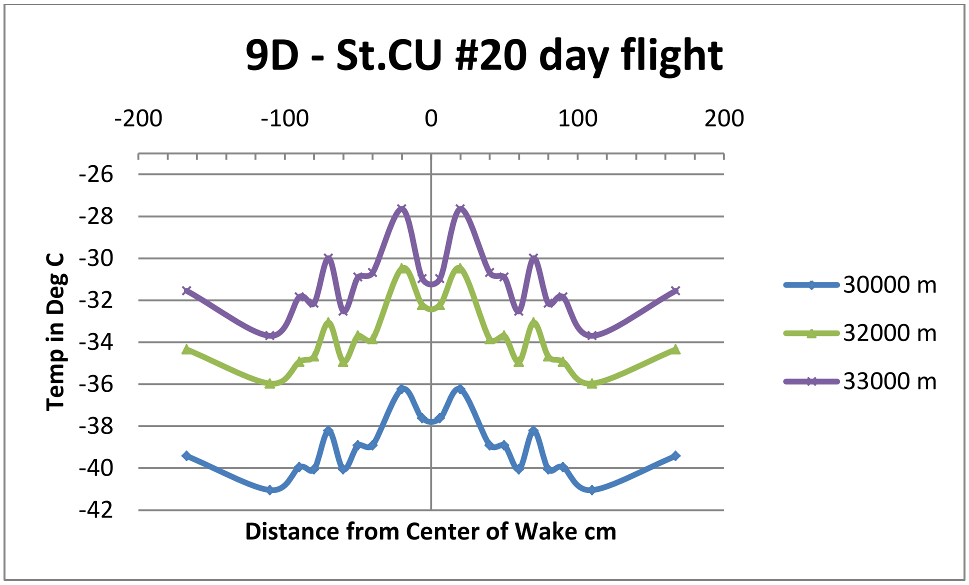


Figure 6. **Temperature vs. distance from center of boom and how wake profile varies with altitude during a day flight**.

Two night missions were flown during the summer of 2013. Data from the first mission is not presented in this paper. Flight 1N was flown on 8-1-13 to investigate the nighttime wake effect. The stratospheric portion of the ascent is shown below.

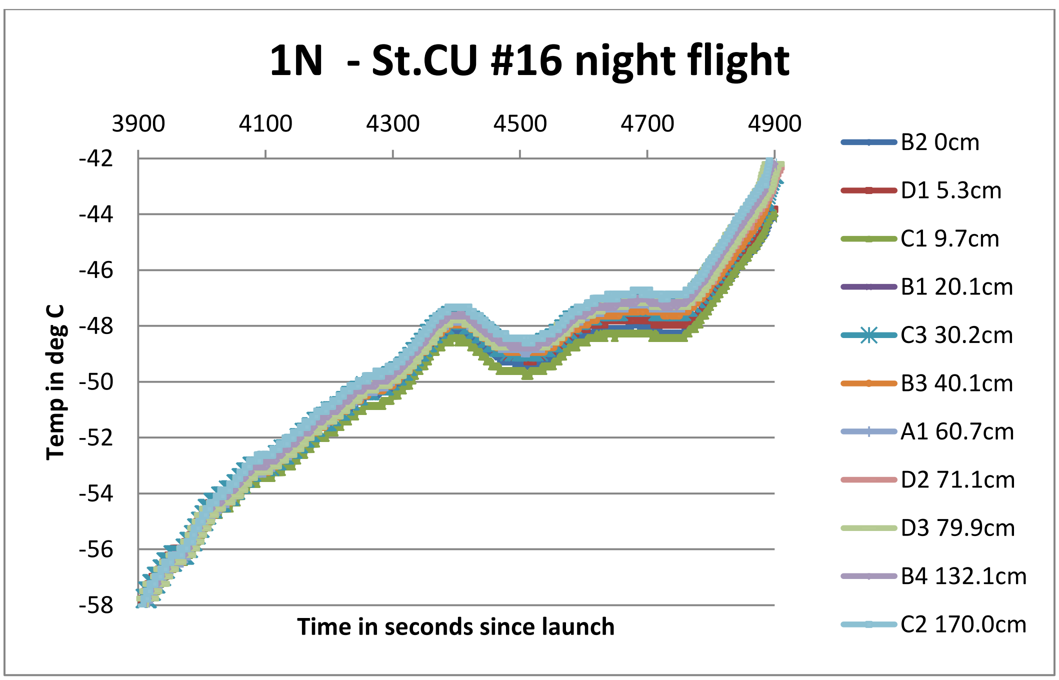


Figure 7. **Graph showing HOBO temperature sensor values vs. time for a nighttime flight conducted on 8-1-2013 – the data encompasses a latter portion of ascent plus burst.**

As was done with the daytime data, Fig. 8 was generated of time slices (and their mirror images) through the temperature data showing the profile of the night time wake. Note the "cold" region (at least 2 degrees Celsius colder) that exists for sensors inside of 50 cm. This region is predicted in Ref. 5. The surrounding temperature is nearly isothermal while the balloon continues to cool adiabatically so the air streaming past the balloon absorbs the energy loss of the balloon gas and creates a cool wake.

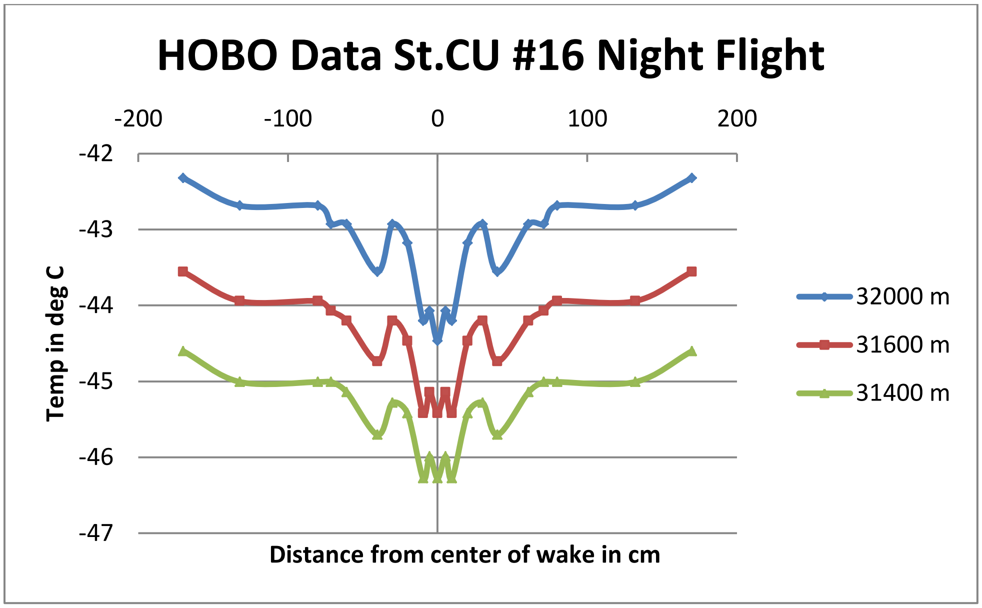


Figure 8. **Distance from center of boom and how the HOBO recorded temperature is different at those positions at 3 different altitudes.**

Here are three time slices through the data from night flight N2 flown on 5-22-14, including one at the moment of burst.

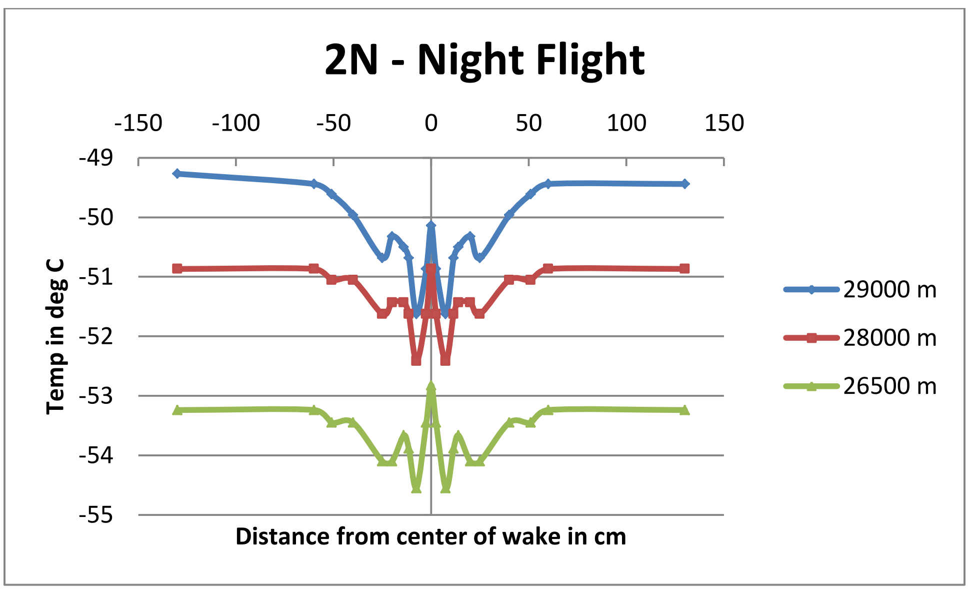


Figure 9. **Distance from center of boom and how the HOBO recorded temperature is different at those positions at 3 different altitudes.**

Data from Fig. 9 shows a colder region generally within about 50 cm from the center of the boom. An interesting feature from this flight was a hot spot from the sensors at 0cm and 2.5cm. We had not seen this elevated temperature in other night flights conducted. It does appear that the central sensors were uniformly warm during the entire flight, so this rise might be due to sensor offsets but, interestingly enough, this feature was not unique to the HOBO temperature sensors.

A new research area this year is was utilizing Arduino microcontrollers to log data from DS18B20 digital temperature sensors. A direct comparison of Arduino-logged data to HOBO-logged at a series of decreasing temperatures is shown in Fig. 10 below from a night flight in which both types of sensors were affixed to the same wake boom.

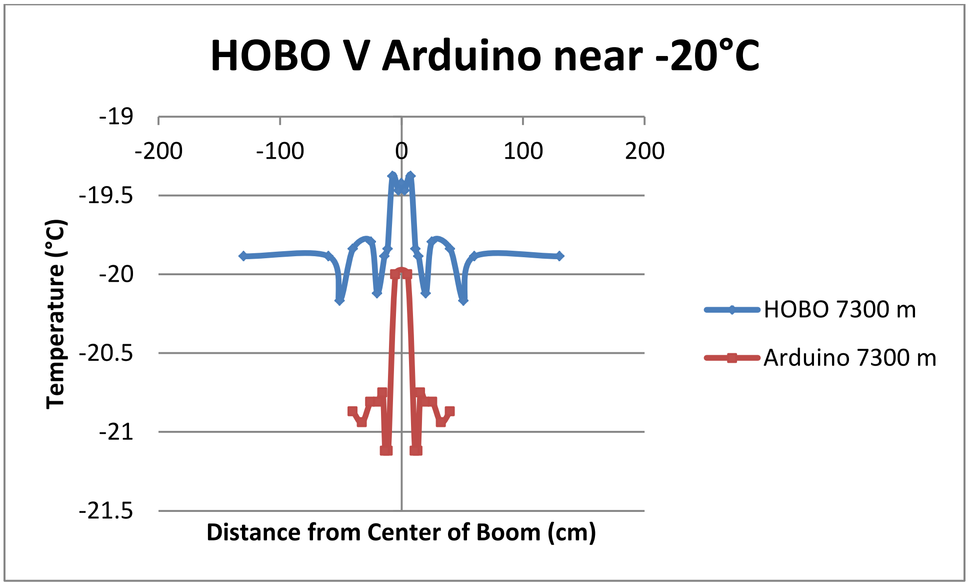


Figure 10A: **Comparison plot of two temperature sensor systems at 7300 meters, reading a temperature of -20 Celsius, during an ascent.**

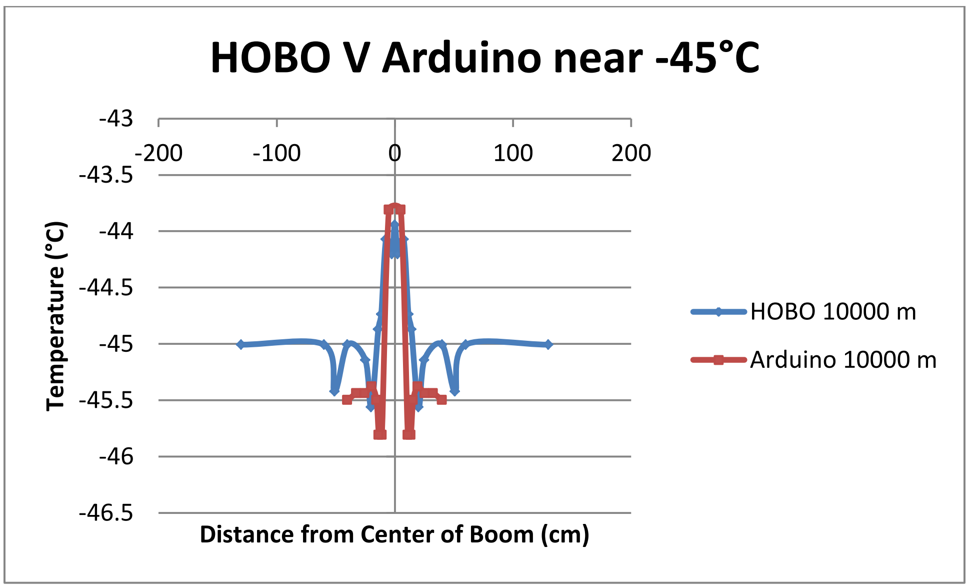


Figure 10B: **Comparison plot of two temperature sensor systems at 10, 000 meters, reading a temperature of -45 Celsius, during an ascent.**

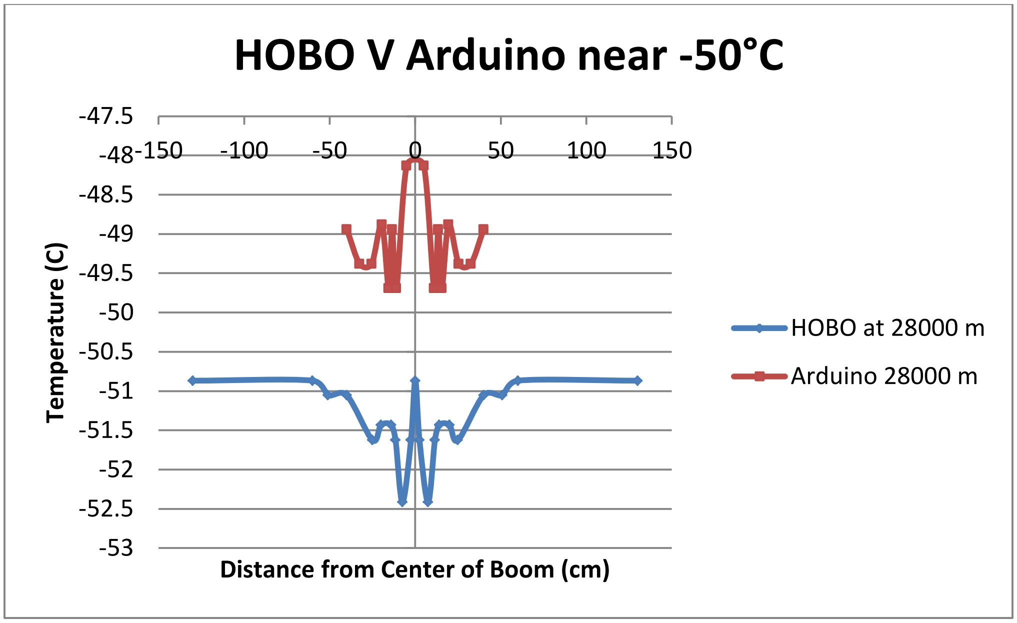


Figure 10C: Comparison plot of two temperature sensor systems at 28,000 meters, reading a temperature of -50 Celsius, during an ascent. This graph is near burst.

An interesting trend occurs around 10,000 meters. The two temperature data sets are very close to one another (within 0.1degrees C), at least in the central region. We seem to see a central region that is warm for both types of data logging devices. We expected to see a cold region in the central axis, but for this particular flight we see both sets of sensors registered a warm central area. It is clear that the temperature drops off and becomes "cold" outside of 5 cm from the central axis. (Note that this is below the tropopause, but at this altitude the sensors are reading approximately the same value). If we look lower in the troposphere we see that the HOBO sensors consistently read warmer than do the Arduino counterparts. As we look at data from the stratosphere, we see that the Arduino sensors consistently read warmer than the HOBO temperature sensors. To be clear, the manufactures specifications for both Arduino[8] (-55C) as well as HOBO temperature sensor[4] (-40C) calibrated range can be an important consideration in the interpretation of the data presented in figure 10. This effect could be explained as a sensor drift effect with respect to temperature, in that the two sensor sets just happen to correlate well at -45 degrees Celsius. Ground testing under cold conditions will be done very shortly to attempt to test this variable.

Another interesting characteristic of the data is that even though this is a night flight (sun effects can be eliminated), we note an edge of box effect: the box width is 22 cm and sensors nearby (HOBO 25 cm and 20 cm and Arduino sensor at 19.5 cm) register warm readings. This was consistent throughout data from the stratosphere and also occurred at lower altitudes, though to a lesser degree.

Comparison could be done between the two sensors closer to the end of the ascent. As figure 11 shows, at 25,600 meters, a comparison was done looking at HOBO data versus Arduino data. The edges of the box are located at +/-11 cm.

Lessons learned from 1-D wake boom dual-sensor-type flights.

Crosschecking varied temperature sensors is a worthwhile endeavor. A logging system that is clearly rated to operate down past -100 degrees Celsius are part of future planned experiments, to check calibration and drift associated with both of these sensors systems. We also need to increase the number of Arduino sensors that fly on the 1-D wake boom to see the spatial profile in more detail and gather more data clearly outside of the wake, more than 50 cm from the central axis.

Results from the X-Boom flight 1X

Results from the first flight of the X-boom were mixed. Minimizing rotation by tying the X-boom firmly to neck of the balloon from multiple directions worked very well. Out-looking video from the camera below the X-boom shows relatively little rotation near burst. (See https://www.youtube.com/watch?v=hxApfU8DqUs.) Pay attention to the lack of rotation of the background at altitude, not the "Goldy Gopher" mascot in the foreground (cute though he may be!).

The up-looking video monitoring the boom and balloon also did well, showing the entire ascent, burst, and part of the descent. We were able to "dial back the clock" from burst to times when the sun was directly aligned with each of the 4 arms in turn, helping focus our search for asymmetry in the thermal wake temperature distribution.

Unfortunately the parachute failed to come out of the basket (despite successful ground testing), perhaps because the solid bottom of the basket prevented the airflow from dislodging it. This did not impact the experimental data directly, but the X-boom was severely damaged upon landing, requiring a complete re-build before Flight 2X.

Regarding the temperature sensors, only one sensor on arm C operated for the duration of the flight, and the "prime" sensors failed as well, so our analysis is exclusively based on arms B and D (opposite one another) and arms A and B (perpendicular to one another). Arms A and B were logged by one Arduino and arms C and D by another, so we identified launch and burst in the data record to help synchronize the two clocks and compensate for logging-time drift. Figure 13 below showing the 8 temperature sensors on arm A versus time is typical.

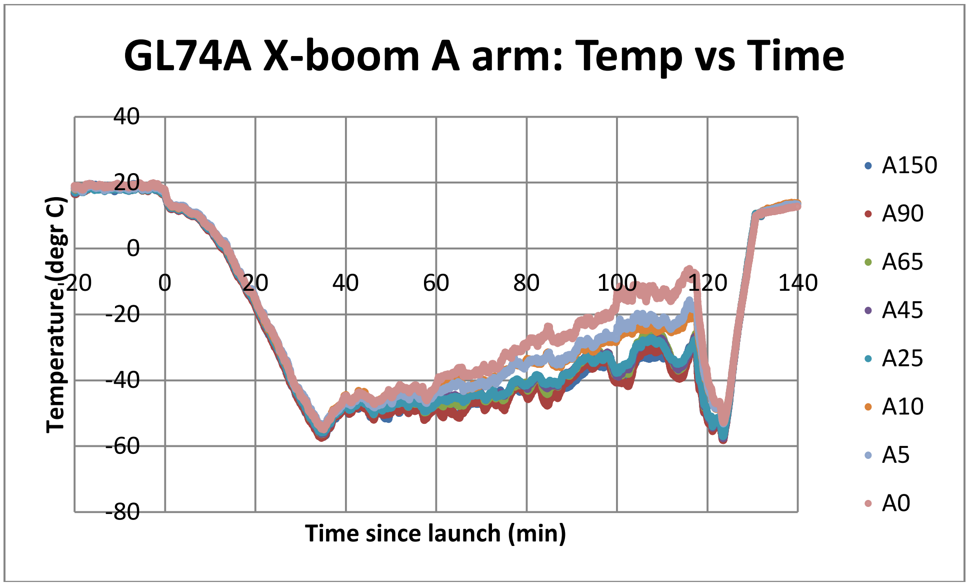
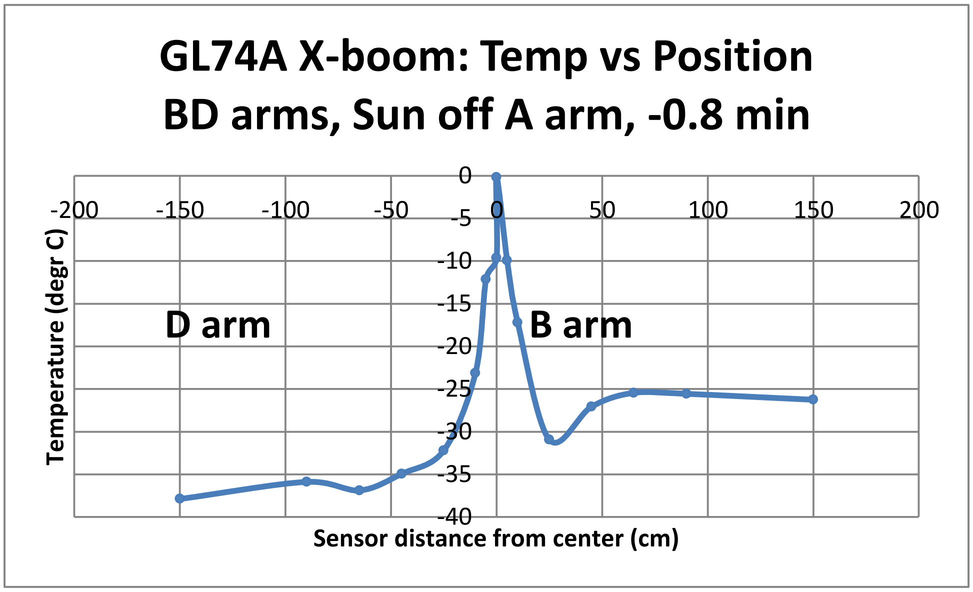


Figure 11. Temperatures from 8 sensors on one arm of the X-boom during Flight 1X. The temperature differences in the stratosphere were much larger than expected and may be due in part to the proximity of the payload box enclosing the Arduino data loggers.

All sensor values are similar until entering the stratosphere (when the temperature starts to increase), at which point they diverge more and more, differing by an astonishing 22º C (on average) between the central sensor (warm) and the outside sensor (cool) for 10 consecutive minutes late in the ascent.

Using the video, we were able to determine when the sun was directly off each arm closest in time to burst. Figure 13 A and B show the temperature profile on arms B and D when the sun was off arm A 0.8 minutes before burst (so B and D are expected to be symmetrical) and when the sun was off arm B 2.7 minutes before burst (so the wake is expected to be warmer on the B side).



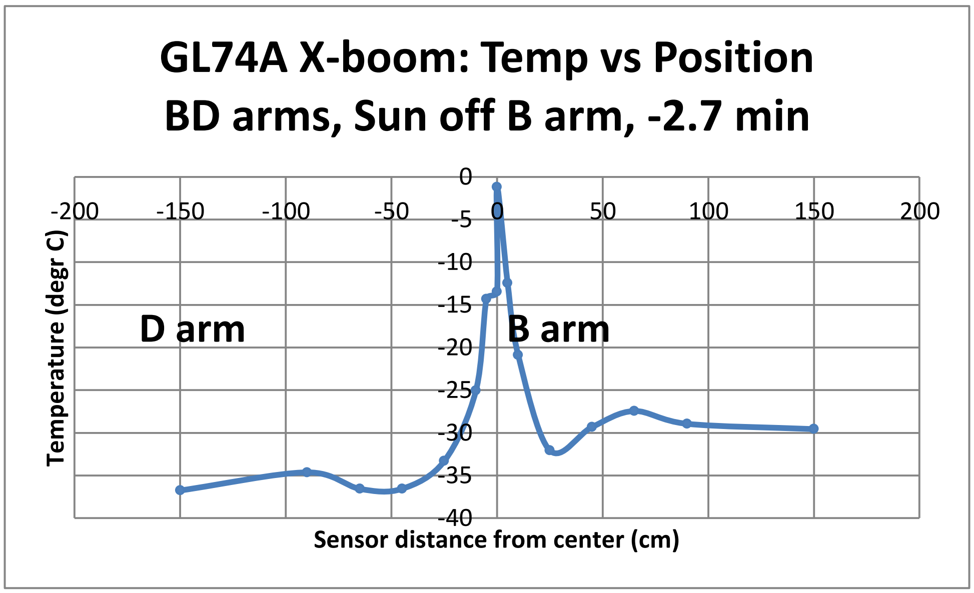


Figure 12. Temperature profile along the BD-arm line of the X-boom (A) when the sun was off arm A, less than 1 minute before burst and (B) when the sun was off arm B, about two minutes earlier. The central temperature spike may be more than just a wake effect. Wake asymmetry is expected at time (B) but not at time (A), but both appear similar. The unexpected temperature asymmetry on the outer ends of arms might be due to the shadow of the balloon falling on the arms of the boom.

The most striking features of these graphs are (a) the presence of a very warm region in the middle of boom, consistent with a warm wake (but possibly explainable other ways too – see below) and (b) the asymmetry of temperature at the outer end of the boom (remember that the temperature outside of the thermal wake the temperature profile was expected to be symmetrical and cold in all cases). Asymmetry within the thermal wake itself, if present at all, is certainly not very distinctive. Comparison of data from arms A and B when the sun was off one specific arm (see Fig. 14 below), did not definitively show the asymmetry we were looking for so we expect that effect may have been swamped by a box-proximity effect.

Lessons Learned from Flight 1X

Compared to other (1-D) boom flights, the X-boom showed an unexpectedly-large temperature variation between central and outside sensors. Although the temperature profile was consistent with the expected warm wake, the size of the effect suggests that the proximity of the box containing the Arduinos might be exaggerating the effect, even though it was white. This led us to separate the X-boom arms from the payload box vertically by 1 meter using extended cabling for Flight 2X, to help distinguish between wake effects and box-proximity effects.

Also, the sun was nearly overhead during Flight 1X, as seen in Fig. 14, so the warmest part of the balloon was actually on the top rather than a side, presumably reducing potential thermal asymmetry in the wake. The fact that the end sensors on the boom appeared to have some sun-sensitivity (not expected) suggests that parts of the boom might have actually been in the shadow of the balloon itself, especially near burst where the balloon was the largest. This led us to launch Flight 2X near sunset to get sun exposure more from the side and to keep the boom completely out of the shadow of the balloon. We also addressed the parachute basket problem, making a second basket with large holes in its floor to allow for airflow to dislodge the parachute during the descent.

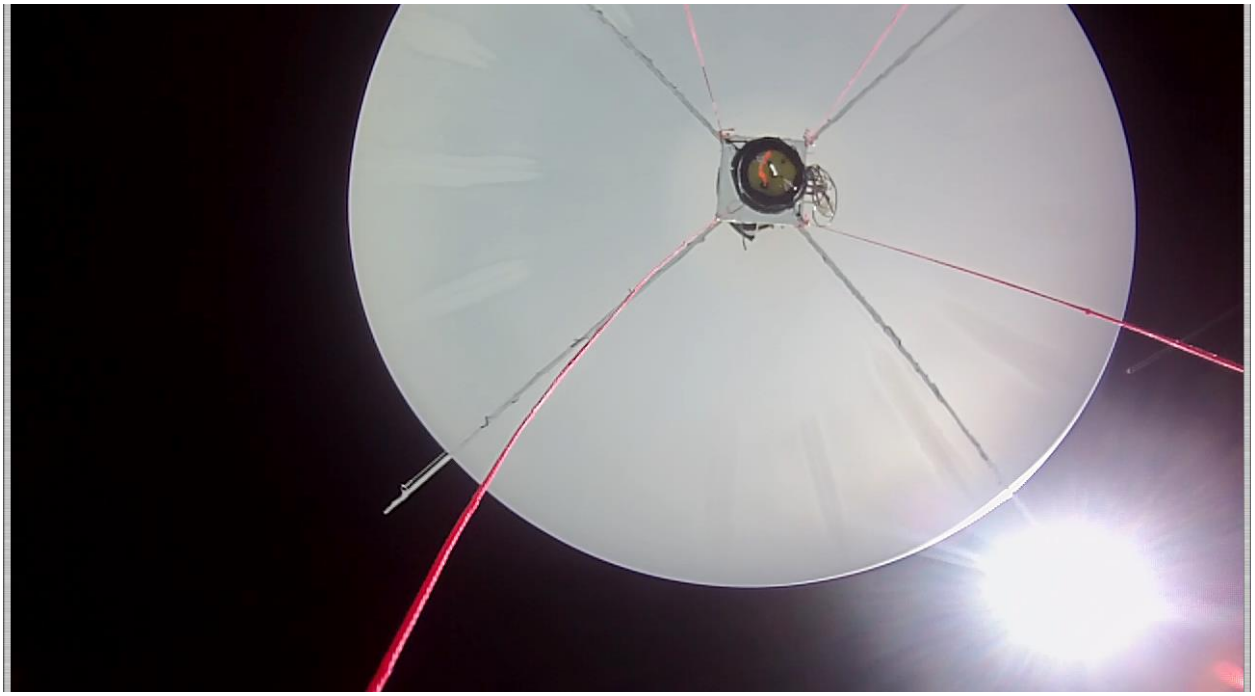


Figure 13. The sun off non-functioning Arm C just under 5 minutes before burst, but mostly shining down on rather than illuminating the side of the balloon, during Flight 1X.

Results from X-boom flight 2X (AKA "GL77")

The X-boom flew to 24,080 meters at sunset on June 3, 2014. For this flight we used a 1600-gram Hwoyee balloon so were again disappointed by this relatively-low burst altitude – we were expecting it would reach at least 27,000 meters based on previous experience with such balloons. This time the sun illumination was definitely from the side (see Fig. 14). Again results from the flight were mixed, but here is a summary of our preliminary analysis of the data.

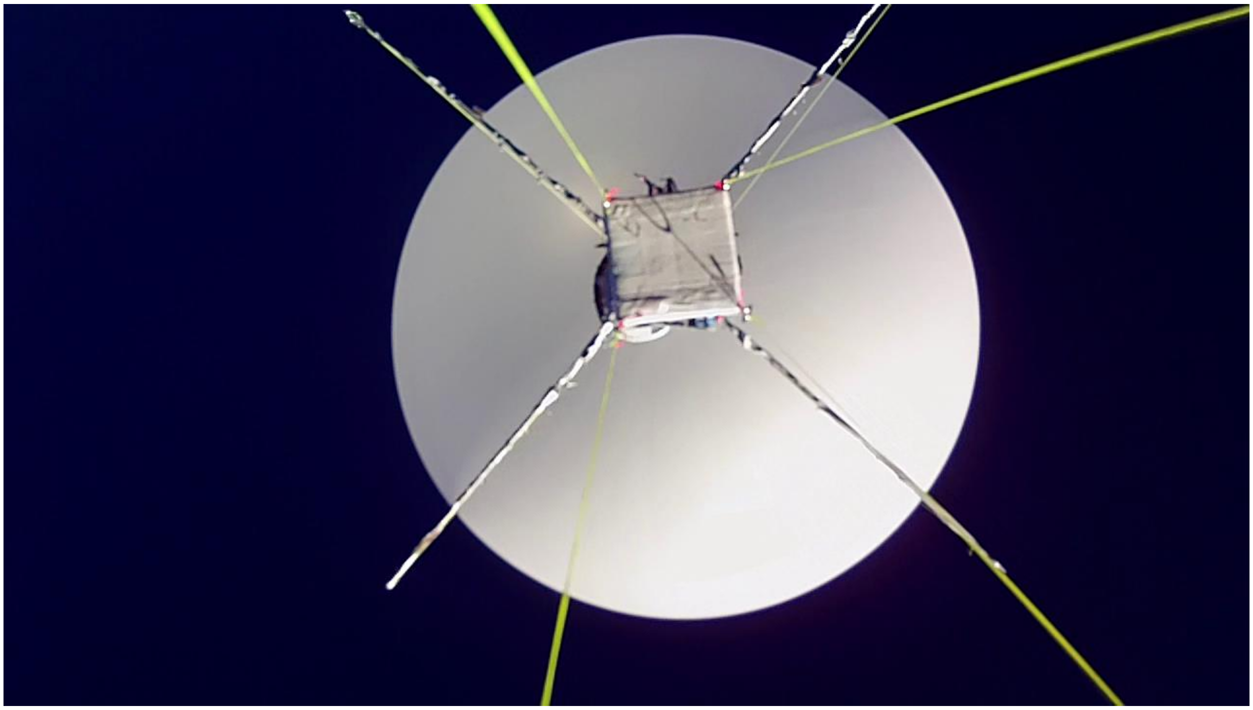


Figure 14. The sun off Arm D on Flight 2X of the X-boom, illuminating the side of the balloon (and even shining up on the *bottom* of the box above the camera) about 60 minutes into the flight but still more than 15 minutes before burst. The video camera stopped working shortly after this frame was taken.

For starters, the parachute deployed properly and the X-boom landed without damage. Unfortunately, the up-looking camera watching the X-boom stopped working about 60 minutes into the flight, just over 15 minutes before burst, so we did not get any footage of the parachute deploying. The anti-rotation solution appeared to work well again, though we did not record out-looking video on this flight. The lack of video during the latter part of the ascent into the stratosphere limited our ability to analyze the data, since we didn't know when the stack was oriented in which direction. One of our tracking units has a magnetometer so on future flights we might log that data as a backup to video for determining orientation.

For this flight the X-boom was detached from the lid of the Arduino payload box and mounted 1 meter higher on the stack, to mitigate potential heating of the boom sensors due to box proximity. All 4 arms operated for the full ascent, though arms B and D (this time logged by the same Arduino) came unplugged during post-burst chaos and hence did not log the full flight. The "prime" sensors (logged by a third Arduino) also logged the full flight. The "prime" sensors were located in between the regular sensors, but not on all 4 arms, to give us better spatial resolution. Their purpose was to help us decide whether or not the standard sensor spacings were or were not adequate to see the salient features of the thermal wake.

Figure 15A below shows the 8 temperature sensors on arm A versus time strikingly different from Fig. 12 from flight 1X. On flight 2X the temperature above the tropopause did not increase much at all. The sensor values basically agree until entering the stratosphere, after which they start to diverge (see close-up Fig. 15B), but there is only a 0.8º C difference (on average) between the central sensor and the outside sensor for 10 consecutive minutes late in the ascent. Very unexpectedly, the central sensor is *cooler* that the outside sensor, suggesting the possible onset of a night-time cold wake effect (or else calibration issues between the sensors). Time slices at 65, 70, and 75 minutes into flight (just before burst) do not show a clear thermal wake (see Fig. 16). It is tempting to conclude that the larger temperature spread during the earlier flight was due to a box-proximity effect, but the time-of-day might have been a major contributing factor as well, since sometime in the vicinity of sunset presumably the thermal wake effect switches from a warm wake (daytime effect) to a cold wake (nighttime effect), so that may partly explain the lack of a significant thermal wake during flight 2X.

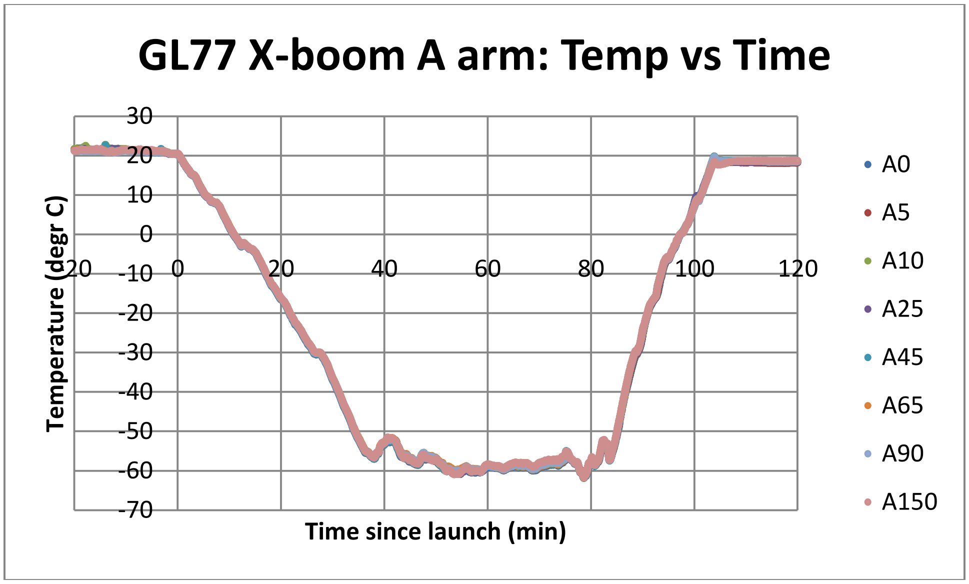


Figure 15A. Temperature of the 8 sensors on the A arm during flight 2X. The temperature in the stratosphere was fairly constant above the tropopause and the temperatures at different parts of the boom did not vary from one another nearly as much as during flight 1X.

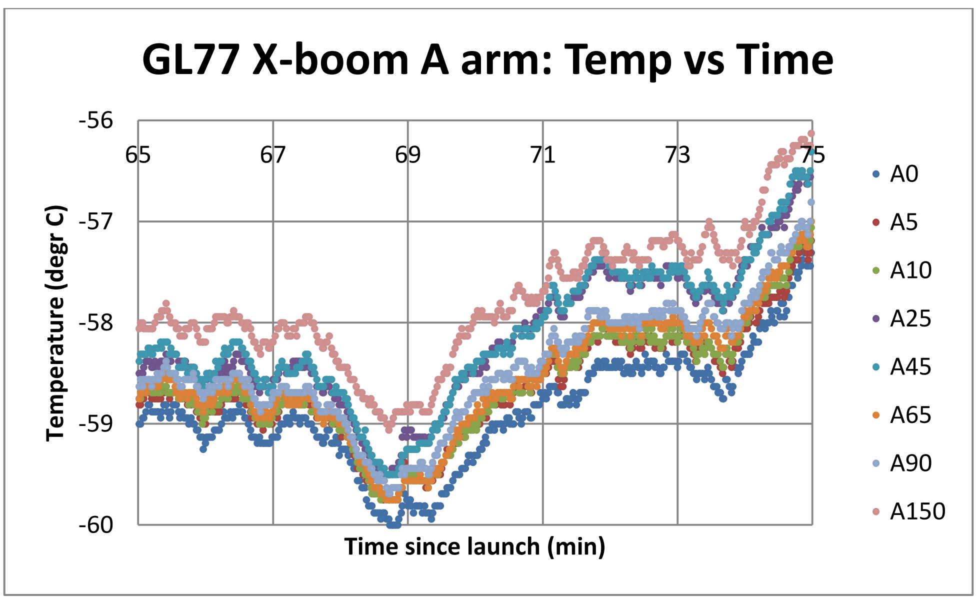


Figure 15B. A zoom-in of the data late in the ascent for flight 2X. There is a persistent difference in readings between temperature readings, but it was not in the expected (spatial) order.

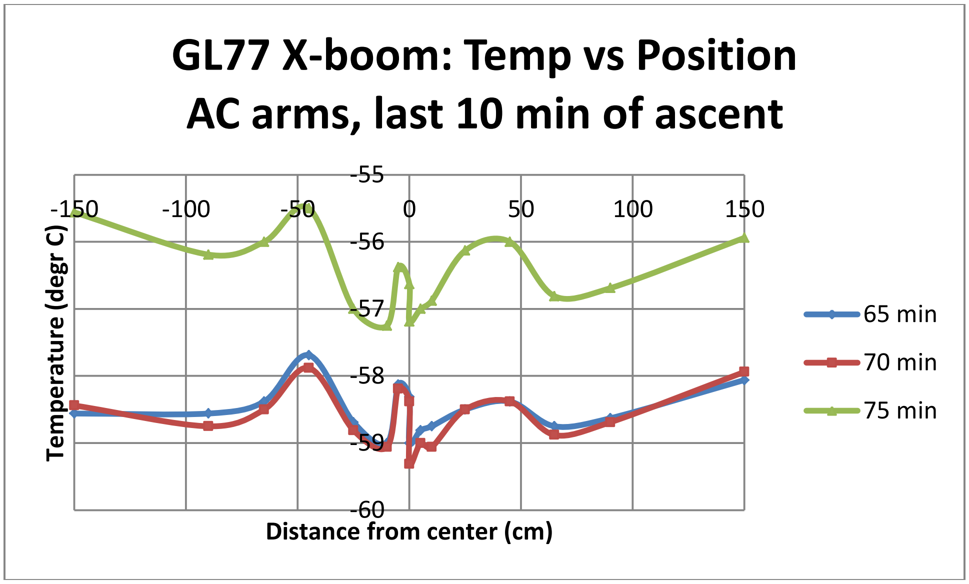


Figure 16. **Attempting to image the thermal wake using sensors on arms A and C late during the ascent during Flight 2X. The structure here has a surprising shape but seems to persist over the full 10 minutes. This may be due to calibration differences between the sensors rather than to the wake effect.**

VI. Questions for summer 2014 consideration

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

A.1.1. How does geometry of the sensor affect the readings? -.i.e.- Spherical sensors have a different profile versus cylindrical ones (6) a cylindrical thermometer: F = Power conducted per degree temperature difference between thermometer and air/ Power radiated per degree temperature difference between thermometer and black body temperature

$$F = \frac{K}{4\sigma T^3 \epsilon} \frac{1}{R ln \frac{L}{R}}$$

where K is the thermal conductivity of the air, σ is Stefan Boltzmann constant, ε is the IR emissivity, R the radius of the probe, and L the length of the thermometer. Ref 6 state that a spherical thermometer will have a larger figure of merit and will therefore be a more effective thermometer.

A.1.2 How do ultrasonic sensors operate in a near space environment? Can they be used to measure the thermal wake?

A.1.3 What can we learn about offsets created at very low pressures occurring later in the flight?

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 in terms of the thermal wake effect?

What can be learned from high-definition video footage taken from wake boom flights?

C.1.1. How much further refinement of the spatial extent of the wake will be possible if video is used to calculate the volume of the balloon?

VII. Conclusions

Our thermal wake investigation continues to evolve, with regular surprises in the data and nearly every flight suggesting new ideas for how best to make the measurements. Both HOBO-logged air/water/soil temperature sensors and Arduino-logged digital temperature sensors appear to be sensitive enough to measure thermal wakes both in the daytime and at night (with Arduino systems costing much less) though the two types of sensors do not agree with one another over the entire temperature range experienced in near-space missions. We plan to add thermocouples to our sensor portfolio in the near future since they have a much lower operating range, though they are pricey.

We still appear to be suffering from box-proximity issues during day flights (despite our mitigation attempts using white payload boxes and white boom structure) *and* during night flights (which was unexpected). Vertically separating the sensor-boom from the lid of the payload box containing the data loggers can be done with Arduino systems, but not with the pre-wired HOBO temperature sensors, giving us even more pause regarding continuing to use HOBOs.

A X –shaped wake – boom is an interesting way to attempt to experimentally measure temperature anisotropy in a thermal wake. The X-boom has given us significant challenges, not the least of which is the fact that it must be assembled on the flight line because it is too large to be transported in one piece. Arduinos can be finicky; especially when one uses them to log data from up to 20 sensors each, and all the cabling must be done by hand and is hard to keep intact through descent (and ascent) turbulence. We plan to rebuild the Arduino box for the X-boom system so that all connections can be made on the outside, after the box has been sealed, and all connections can be held down with tape or zip ties (rather than hot glue, which can get brittle in flight).

We have now settled on using the same type of balloon (1600 gram Hwoyee) for all wake flights, but experience flying the X-boom at two different times of day points out another variable we didn't think to control for. The thermal asymmetry we sought may well go away due to shadow-geometry during a mid-day flight (i.e. when the sun is overhead rather than on the side), but we remain surprised that our sunset flight did not exhibit a distinctive warm wake, suggesting that perhaps a non-midday-sun might not be intense enough to overcome the natural tendency of balloons to form a cold wake (i.e. the nighttime effect).

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