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PRESSURE, HUMIDITY, TEMPERATURE MEASUREMENTS AND LONG-RANGE RADIO TRANSMISSION USING LAACES BALLOON

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The goal is to get a range of atmospheric data gained using temperature, pressure, humidity sensors placed on the payload for altitudes ranging from 0 to 100,000 feet above sea level. The payload stores data onto an SD card while simultaneously transmitting measurements back to the chasing team using a 900 MHz quadrifilar helix antenna. The payload's construction consists of two polystyrene layers which limit the heat transfer as the balloon is ascending. The total mass of the payload is 496 g. Electronics were completed with sensor interface, data acquisition, data storage, data transmission, and power supply. All three types of sensor were calibrated. Power consumption was also calculated and power is supplied by a 2CR5 camera battery. Software for the project was developed for the Arduino Due and XBee module and included functionality for storage and communications. A vacuum chamber was built for vacuum test and pressure sensor calibration. Impact tests conducted from a 1.8-meter height saw the payload unharmed after landing at a speed of approximately 4 to 6 m/s. The payload was also put in a –80 °C freezer for thermal testing. Long range antenna testing was performed on two fire-lookout-towers in Pitkin, Louisiana. Balloon launches were conducted in the NASA CSBF on May 24 and May 25, 2016. The payload was safely recovered and data was retrieved from the SD card and successful antenna transmissions on both flights. The speed of sound as a function of altitude was be calculated using the measured temperature, pressure, and humidity data.

Keywords: balloon payload design, atmospheric data, long-range data transmission, thermal isolation, speed of sound profile

1. Introduction

LaACES (Louisiana Aerospace Catalyst Experiences for Students) is an undergraduate research project sponsored by the Louisiana Space Consortium. The goal is to design, develop, and operate a balloon payload to measure atmospheric data including temperature, humidity, and pressure as functions of altitude up to 100,000 ft (about 30 km). The payload should not exceed 500 g due to the FAA weight regulations. The speed of sound can then be calculated using these measured data.

The team consists of five students: two mechanical engineering, one electrical engineering, and two computer science majors. The LaACES committee of seven faculty members provided a series training sessions in the fall of 2015 semester. The student team conducted preliminary design and also built a vacuum chamber over the Christmas break. After the spring semester started, the team worked together a few times a week and met with the LaACES committee every Monday for 30 minutes. The payload was launched twice on May 24 and 25, 2016. The payload successfully recorded the measured temperature, humidity, and pressure data to the micro-SD card and also transmitted data using a 900 MHz quadrifilar helix antenna. In the second launch, 80% of the data were received by a Yagi antenna when chasing the balloon. In addition, the payload was still recording and transmitting data after a 12.5-hour recovery.

2. The Speed of Sound as A Function of Altitude

One of the major acoustical properties of atmosphere is the speed of sound which is correlated to temperature [1]. According to the ideal gas law, the speed of sound formula is [1, 2]

$$c = \sqrt{\frac{\gamma RT}{M}} \tag{1}$$

where γ is the ratio of the specific heat of the fluid, R is the gas constant of the fluid, T is the absolute temperature (K), and M is the molecular mass (kg/kmol).

This formula is sufficient for calculating the speed of sound in dry air. However, under humid conditions, the addition of water vapor to the gas mixture will alter the speed of sound due to two effects. The first is an increase in the speed of sound due to a decrease in the average molecular mass of the air, and hence the density, as the water vapor displaces heavier gases. The second is a decrease due to an increase in the average molar heat capacity of the air, due to the high specific heat of water. Dean, in his US Army report, studied that the overall effect is estimated to be about 75% of the density effect [2]. The value found for the mole fraction of water vapor is used to adjust the humid air temperature to a dry air temperature which will result in an equivalent speed of sound. The speed of sound can be calculated using the adjusted temperature:

$$c = 20.06\sqrt{T_s}\ , \tag{2}$$

where T_s is called the absolute sonic temperature given by

$$T_s = T\frac{1+0.1459x}{(1+0.2045x)(1-0.3780x)}\ , \tag{3}$$

and x is the ratio of partial pressure of water vapor to the absolute atmospheric pressure:

$$x = \frac{P_{\text{vapour}}}{P_{\text{abs}}}\,. \tag{4}$$

The absolute atmospheric pressure (in hPa or mbar) P_{abs} can be measured using a pressure sensor.

Since humidity can have a measurable effect, it is necessary to account for the amount of water vapor present in the air in the calculation of sound speed. The quantity of water vapor present in the air at a given temperature is known as relative humidity, which is a ratio of the partial pressure of water vapor in the air to the maximum saturation partial pressure for that temperature [4]. It is given by:

$$\text{R.H.} = \frac{P_{vapor}}{P_{ws}}\,. \tag{5}$$

Relative humidity (R.H.) is measured using a humidity sensor.

The maximum amount of water vapour that air can be saturated with, and the partial pressure it imparts, increases with temperature. Along with a temperature sensor, the maximum saturation partial pressure of the water vapour at a given temperature can be found using the polynomial developed by Herman Wobus [5]:

$$P_{ws} = e_{so} / \rho^8\,, \tag{6}$$

where

$$\rho = (c_0 + T(c_1 + T(c_2 + T(c_3 + T(c_4 + T(c_5 + T(c_6 + T(c_7 + T(c_8 + Tc_9)))))))))\ , \tag{7}$$

and constants $e_{so} = 6.1078, c_0 = 0.00000683,\ c_1 = -0.90826951\times10^{-2},\ c_2 = 0.78736169\times10^{-4}$, $c_3 = -0.61117958\times10^{-6},\ c_4 = 0.43884187\times10^{-8},\ c_5 = -0.29883885\times10^{-10}$,

$c_6 = 0.21874425 \times 10^{-12},\ c_7 = -0.17892321 \times 10^{-14},\ c_8 = 0.11112018 \times 10^{-16},\ c_9 = -0.30994571 \times 10^{-19}$.

It is worth mentioning that the above approximation polynomial was developed based on the older International Practical Temperature Scales of 1948 (IPTS-48). The measured temperatures in this project are on the current International Temperature Scales of 1990 (ITS-90). For the temperature range, although the difference between these two scales is less than 1%, the measured temperatures were converted to those of IPTS-48 in Eq. (7).

From previous studies, the speed of sound profile varies with the season of year, and with latitude. It may change even within one day, especially in troposphere close to the Earth surface. Two minimum values of speed of sound occur around 15 km and 80 km altitudes [1,2].

3. Payload Development

3.1 Vacuum chamber

As the pressure at 100,000 ft (30 km) altitude may be as low as 1 to 5 mbar, it is necessary to test the payload at low pressure to ensure its integrity. A vacuum chamber was made of steel tube of 20-in diameter (508 mm) and 3/8-in thick (9.5 mm). The vacuum chamber is sealed using neoprene gaskets with an acrylic cover on top so one can visualize the inside of the vacuum chamber. As shown in Figure 1, a Cole-Parmer vacuum pump (model WU-07061-11) was used to reduce the internal pressure to 100 mbar without damaging the acrylic cover since the acrylic cover will bend under atmospheric pressure. The vacuum chamber is also equipped with a pressure gauge which is calibrated using an industrial grade pressure calibrator.

Figure 1. Vacuum chamber.

3.2 Electronics and software design

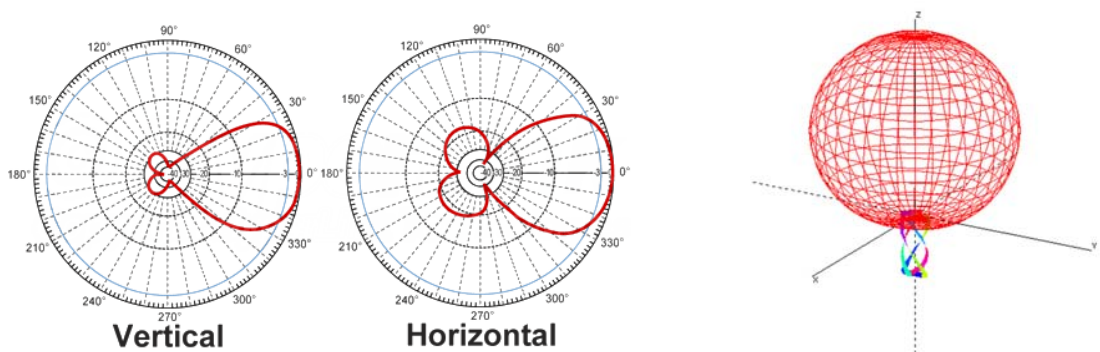
The payload is designed with Arduino Due as the central component. Arduino Due is a 32-bit microcontroller with 12 analogue input channels and a built-in 12-bit ADC. Sensors are interfaced to the Arduino through an external interface board. There are totally six sensors.

- Two humidity sensors: one analog Honeywell HIH-4000 and one digital from AM2302 temperature-humidity sensor.
- Three temperature sensors: two external and one internal. One of the external temperature sensor is based on 1N457 diode because an ordinary PN junction diode can serve as an effective temperature sensor over a wide range of temperatures. The second diode-based temperature sensor is from the AM2302 sensor. The internal temperature sensor is used to verify the thermal isolation of the Styrofoam payload package.
- One Pressure Sensor: UltraStable 1230.

The software is stored on the Arduino Due and begins running on start-up. The flight software has a main loop and two subroutines: one subroutine records the time from a real-time clock while the other logs recorded data to a micro-SD card. A new data record is made every three seconds while transmission happens every second which increased the redundancy of the transmission. The program will continue to log and transmit data until the batteries can no longer support the hardware or the Arduino Due is turned off.

Raw sensor values are stored in a 0-255 range. Then these values are converted to human readable formats in proper engineering units. Data are stored on a 1 GB micro-SD card with UTC formatted time stamps. Transmissions include raw and converted data.

The receiving antenna was chosen to be a 9 dB Yagi type antenna, operating at 900 MHz. This antenna provides 60º beam width in both the horizontal and vertical directions, as shown in Figure 2 (a). For the payload's transmitting antenna, a quadrifilar helix was chosen for its light weight, downward radiation pattern, and circular polarization. Figure 2 (b) illustrates the quadrifilar helix range shape simulated using NEC2, a free antenna modeling software. By using a circularly polarized antenna, the alignment between the transmitting and receiving antenna was not critical, any alignment would cause 3 dB loss. This is in contrast to using two linearly polarized antennas where perfect alignment would cause 0 dB loss, but any misalignment would cause significant signal loss which increases to infinity as the misalignment increased.



(a) (b)

Figure 2. Antenna design. (a) Yagi antenna beam, (b) quadrifilar helix range shape.

Two XBee Pro XSC modules are used on both the transmitting and receiving ends. The XBee module operates between 902 MHz and 928 MHz such that this bandwidth will not interfere with the LaACES communication. The two XBee modules can ideally transmit data over 20-mile distance.

The payload is powered by two 2CR5 lithium batteries in series. Each 2CR5's capacity is 1400 mAh. Power consumption Arduino draws 97 mA continuously and XBee draws 215 mA 6.93 % of time. It is expected that the battery life is 12.6 hours. There are two LED lights routed outside the payload box to reveal the operation status. The green LED indicates writing to SD card is successful while the red LED indicates data transmission through the XBee module and helix antenna is successful.

3.3 System integration

The external structure is composed of two layers of 3/4-inch-thick Styrofoam which is a porous material such that air can flow through the layers and balance inside-outside pressure. The dimensions of the container are 20 cm × 21 cm × 14 cm such that the box is spacious enough for the circuit boards, wires, and batteries. The payload box serves as thermal isolation and shock absorption. It is worth mentioning that the 2CR5 batteries will stop outputting power at –5 °C. Econokote, a heat shrinking skin, was ironed on to the outside of the box for extra structural and thermal support. There are seven holes in the box. Two holes are 17 cm apart at opposite corners of the box on top and bottom with straws in between to route the payload strings. Other holes are for the two LED lights, external temperature sensors, humidity sensor, and the antenna attachment. The total mass is 496 g.

3.4 System tests

3.4.1 Antenna range testing

Although the expected range of the XBee module is 20 miles (32.19 km), it is quite difficult to find 20-mile clear space without interference by trees and buildings. An initial radio communication test was conducted between a stationary transmitting antenna on top of a four-story building and a receiving antenna on a vehicle driving away from the building. Such a test resulted in loss of signal at approximately 1.5 miles. Then a Hata model was built to predict behavior of cellular transmissions in built-up areas by including the tree interference. The Hata model indicated approximately 2.6 km (1.6 miles) maximum transmission distance which agrees with the initial experiment.

Further tests were conducted on two fire-lookout-towers separated by 10.2 miles in Pitkin, LA. The data transmissions between the two antennas were successful.

3.4.2 Vacuum test

Since the payload will experience external pressure drop from atmosphere to almost vacuum in ascent, the payload must be tested in a low-pressure environment for its integrity. The payload box was placed in the vacuum chamber shown in Figure 1. It took about six minutes to reach 100 mbar, and the test at 100 mbar lasted 30 minutes. The post-inspection did not discover any defect on the payload box. In addition, the pressure transducer (UltraStable 1230) in the payload was calibrated in the vacuum test. The average error over the entire test is 0.83 %. Figure 3 illustrates the pressure curve in vacuum test.

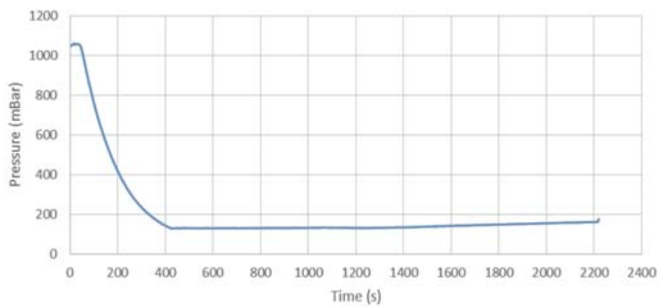


Figure 3. Vacuum test.

3.4.3 Temperature test

The payload was placed in a −80 ºC freezer for about 15 minutes, as shown in Figure 4. The two external temperature sensors are both diode based. However, one is powered continuously (blue curve), while the other one is pulsed on for 50 ms during data collection (red curve). It is discovered that the continuously powered diode would radiate heat itself, which affects the test results. The internal temperature (yellow curve) barely drops below 5 °C, which means the thermal isolation of the polystyrene box is sufficient.

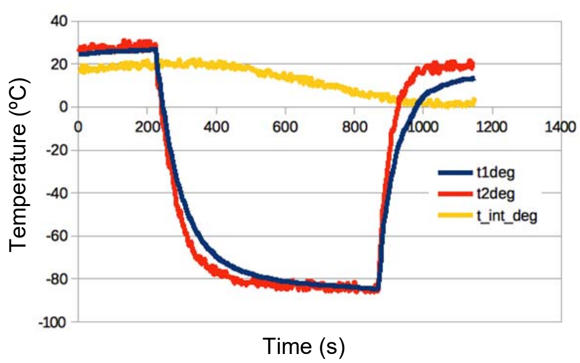
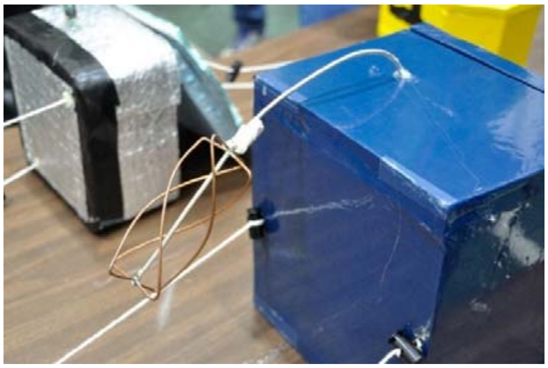


Figure 4. Temperature test.

4. Payload Launch

Two balloon launches were carried out at the NASA Columbia Scientific Balloon Facility (CSBF) in Palestine, TX on May 24 and 25, 2016 at about 6:30 AM. A typical payload configuration consists of a latex sounding balloon (filled with helium), a parachute, the cut-down command module, ham radio beacons and GPS modules for the chasing and locating purpose, cameras, and a few experimental payloads. The entire flight typically takes about 2.5 to 3 hours between take-off and landing. Figure 5 illustrates the payload before launch with the quadrifilar helix antenna pointing downwards (a), and the hand-held receiving antenna during the flight (b).



(a)

(b)

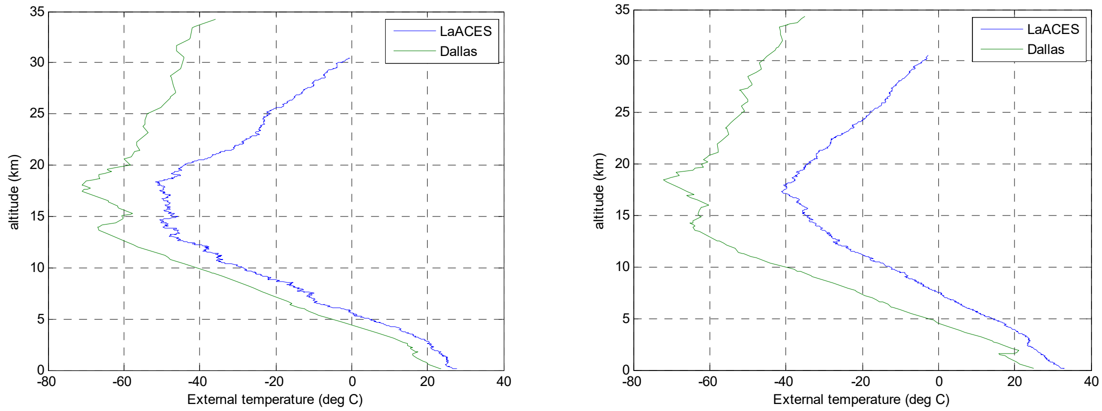
Figure 5. (a) payload on strings before launch, (b) hand-held receiving Yagi antenna.

On May 24, the transmitter sent 1997 measured data after take-off, but only 147 packages were correctly received, and the data transmission was totally lost after the balloon reached 11,482 ft altitude. After recovery, it is found that the antenna helix is damaged and the XBee module was loose.

On May 25, a different transmitter antenna (892 MHz) was used and the XBee module was secured to the Arduino board using a lock tie. This time the transmitter sent 1915 measured data between take-off and landing, and 1520 packages were correctly received. The success rate is 80%. Data transmission was almost continuous even when the balloon reaches the highest altitude (about 19 miles) which agrees with the simulation and satisfies the 20-mile design specification. It is worth mentioning that after recovery at 7 pm (12.5 hours after initial powering), payload was still writing to the SD card and the transmitter was still working. Battery voltage was 11.07 V after recovery. In addition, the payload's internal temperature was never below 2 °C. So, the thermal isolation was successful.

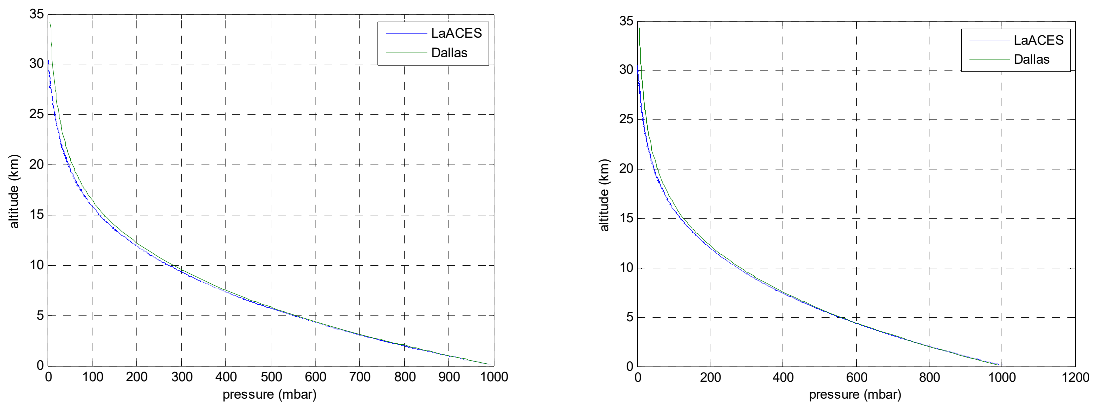
5. Results and Discussions

In both launches, the payload successfully measured the temperature, pressure, and humidity signals and stored the data in the micro-SD card. Figure 6 through Figure 8 below show the recorded data of both launches. These data are also compared with the counterparts measured by the NOAA weather balloon at the Dallas station, which is the closest weather station from the CSBF, on the same day launched at 6:00 AM. Although the measured external temperature does not exactly agree with the Dallas data, they are in the same trend. The discrepancies are possibly because Dallas is 122 miles (about 200 km) north from the CSBF and the LaACES launches are about 30 minutes later. It can be seen in Figure 7 that the measured pressure data agree very well with the Dallas weather balloon data. As illustrated in Figure 8, the measured humidity data reasonably agree with the Dallas data. Humidity follows expected increase, sharp drop, increase, and then drop to roughly 1%. The increases indicate that the payload crossed clouds. Later we noticed that the humidity sensor is light sensitive but the influence of the light intensity was not considered in calibration.



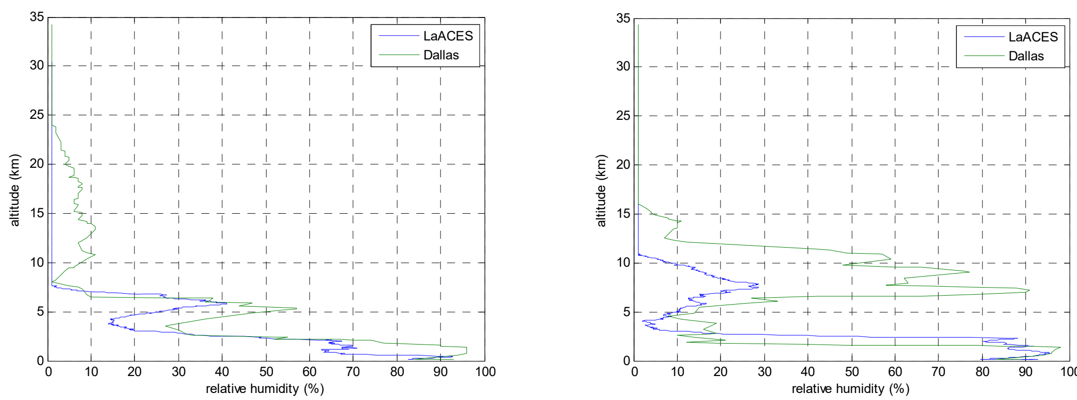
(a) May 24, 2016 (b) May 25, 2016

Figure 6. External temperature data.



(a) May 24, 2016 (b) May 25, 2016

Figure 7. Ambient pressure data.



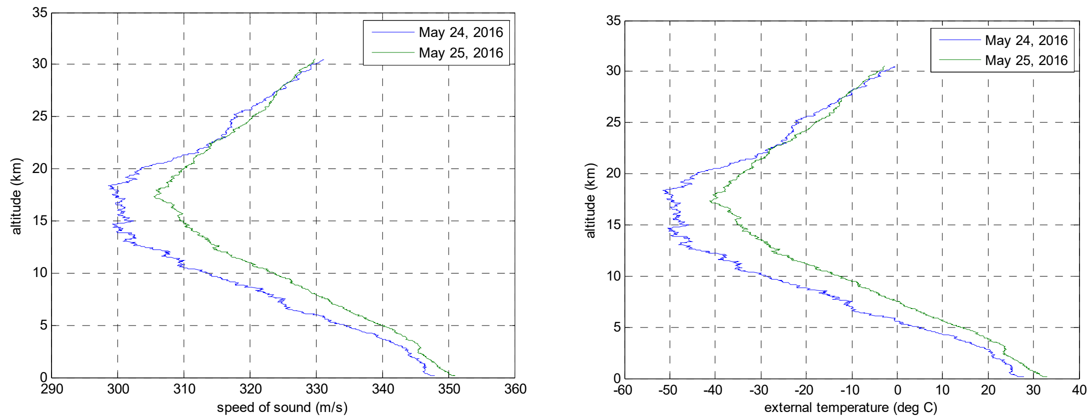
(a) May 24, 2016 (b) May 25, 2016

Figure 8. Humidity data.

The speed of sound is then calculated using the formulas shown in Section 2 above. Figure 9 (a) shows the calculated speed of sound profiles of both launches. It can be seen that minimum speed of sound occurs around the 15 km altitude, which agrees with previous studies.

For comparison, Figure 9 (b) shows the measured external temperature in °C. These two figures show quite strong correlations. To study the influence due to humidity, a ratio is taken:

$$\frac{\sqrt{T_{\text{kelvin}}}}{c} = \frac{\sqrt{(1+0.2045x)(1-0.3780x)}}{20.06\sqrt{1+0.1459x}}. \tag{8}$$



(a) calculated speed of sound profiles (b) measured external temperature

Figure 9. Calculated speed of sound and measured external temperature of both launches.

Figure 10 shows the variation of the ratio – only 1/500 throughout the 30 km altitude. It means that pressure and humidity has little influence on speed of sound. Temperature is the major factor for the speed of sound profile. At high altitude (> 10 km) humidity decreases to 1%, so the ratio is essentially constant. There are some variations for low altitude due to higher humidity.

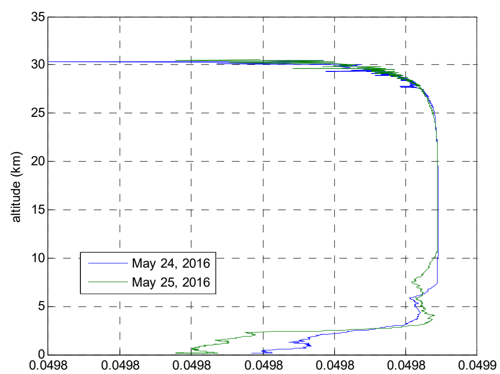


Figure 10. Ratio of $\sqrt{T_{\text{kelvin}}}\,/\,c$ as function of altitude.

6. Conclusions

A balloon payload was designed and built to measure temperature, pressure, and humidity as functions of altitude. In the meantime, the payload transmits data through a 900 MHz Xbee module and a helix antenna to a receiving antenna on the chasing vehicle. Data were successfully collected and transmitted. The speed of sound profiles up to 30 km altitude were calculated accordingly. The calculated speed of sound profiles agree with previous research.

In future research, sound emitter and microphone will be implemented along with a high-speed clock to actually measure the speed of sound profile.

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