The Pressure, Humidity, And Temperature – Tests and Camera Observations (PHAT-TACO) Student-Built Balloon Payload

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Team Philiosohook is a team of five undergraduate students at Louisiana State University (LSU) who developed the "Pressure, Humidity, and Temperature – Test and Camera Observations (PHAT-TACO)" payload to characterize the atmosphere as a function of altitude, correlate temperature and humidity variations with clouds and relate the measured pressure with balloon diameter. The payload consisted of an external temperature and humidity sensor, an internal temperature sensor, a pressure sensor, an High Definition (HD) camera, plus a controller board with a Parallax BasicStamp CPU, a four channel ADC, a real-time clock and an EEPROM for on-board data storage. The camera pointed upwards to image the balloon and determine when the payload entered and exited clouds. The payload was launched at the Columbia Scientific Balloon facility in Palestine, Texas on May 24, 2011, and here we describe the payload development and present the flight results.

I. Introduction

This paper provides an overview of LaACES and describes the results of an experiment designed and implemented by a group of undergraduate students at LSU. LaACES is a program designed to address the issue of the decreasing number of new aerospace workforce candidates by attracting new students to aerospace related programs and providing interdisciplinary training on how to design, build and manage aerospace payloads, using a balloon system to reach "near-space."

At altitudes up to 100,000 ft., a balloon payload passes through the Troposphere, Tropopause and Stratosphere. The Troposphere contains most of the gas in the atmosphere, controls the 'weather,' and contains the clouds. The temperature decreases from an average of 17 °C at the surface to about -60 °C at the Tropopause.[1] The temperature in the Stratosphere then increases from -60° to near zero °C, starting at the Tropopause and ending at the Stratopause, due to the presence of the ozone layer. The ozone layer absorbs the ultraviolet radiation from the sun and causes the increase in temperature.[2]

The mission goal for the PHAT-TACO experiment was to study these layers of the atmosphere using an instrumented sounding balloon flown in East Texas during May and to analyze the environment surrounding the payload. The science objectives were to characterize temperature, pressure, and humidity in the atmospheric layers, and determine when the payload passed through clouds. In addition, the payload measured the balloon diameter as a function of pressure/altitude.

Clouds are important. There are two major types of clouds. The first type, clouds of vertical development, form because of the condensation of rising air. The second type, layered clouds, form because of the condensation of non-rising air.[3] Due to the difference in cloud composition, if the payload passed through a low cloud we expected the humidity to increase drastically but the temperature to remain relatively constant. If the payload passed through a high cloud, we anticipated the humidity to be mostly unaffected and the temperature to drop because of the surrounding ice crystals. Thus, we included a HD camera to monitor the clouds.

Pressure, Temperature and Humidity are parameters that are monitored globally for meteorological use and for weather prediction. This provided a benchmark for comparison of the PHAT-TACO results. As an example, for May 23, 2011, data collected by the National Oceanic and Atmospheric Administration (NOAA) at Ft. Worth, Texas are shown in Fig. 1[4]. In this paper, we demonstrate that the relatively simple PHAT-TACO payload was able to obtain results, over Palestine, Texas, quite comparable to the expectations in Fig. 1.

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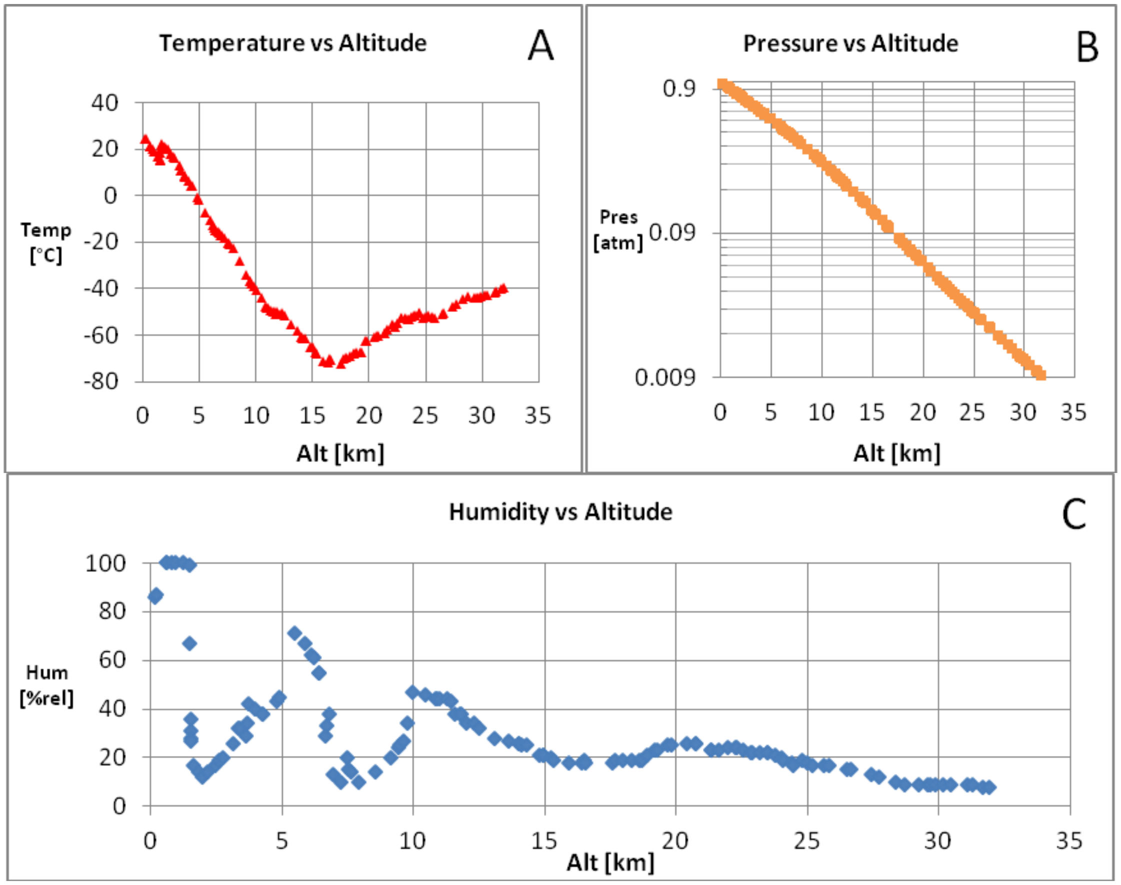


Figure 1: Temperature (A), pressure (B), and humidity (C) as a function of altitude from NOAA.

II. The LaACES Framework

LaACES is based upon the National Space Grant Student Satellite Program "Crawl, Walk, Run, Fly!" methodology. It closely ties cross discipline content knowledge with extensive hands-on experiences to instill skills that are then applied by the students to design, document, build, test and operate a small balloon-borne scientific payload. The long-term goals of LaACES are to 1) attract new students to aerospace related science and engineering programs, 2) provide students with a background to develop and manage modern aerospace projects, 3) give students practical experience with sensors, electronics and "spacecraft" systems, and 4) assist in retaining these students by exciting their imagination and fostering their innate curiosity. In order to accomplish these goals the Student Ballooning Course[5], developed for LaACES, spends the fall semester covering the four major topics of electronics, programming, ballooning and project management. These lessons involve a diverse array of topics from soldering techniques, to sensor signal conditioning, to reading a real-time clock and to mechanical design, thermal control and risk management. During the spring semester, student teams focus on building a balloon payload using the knowledge and techniques learned during the fall semester. The LaACES program is discussed in more detail elsewhere at this conference.[6]

III. The PHAT-TACO Payload

Achieving the mission goal and scientific objectives outlined for PHAT-TACO required meeting the following technical objectives: (a) record Temperature, Pressure and Relative Humidity for the duration of the flight, (b) determine at what altitude the payload enters and exits clouds, and (c) determine the radius of the balloon at several altitudes. Our requirements, derived from our objectives, were to 1) measure temperature, pressure, and humidity every six seconds, 2) identify cloud passages and determine any effects on temperature and humidity, 3) fly both an internal and external temperature sensor to measure temperatures between $^{+}30$ and -70 °C with an uncertainty of ±

0.6 ºC, 4) use a sensor to measure pressure between 1 and 0.008 atm with an uncertainty of ± 0.004 atm, and 5) have a humidity sensor to measure humidity between 100 and 0 % relative with an uncertainty of ± 3% relative.

A. System Design

The payload required four sensors, one to measure external temperature, one to measure internal temperature, one to measure pressure, and one to measure humidity. The basis for choosing sensors included cost, sensing range, accuracy, mass, and ease of integration.

The individual sensors output an analog signal to the sensor conditioning and control board, which changed the outputs to 0-3V signals, as input to the ADC. The ADC converted the signals to a digital format, which were saved to the EEPROM. The sensor conditioning and control board contained the controls for the camera recording and power. There were two separate power supplies: one for the sensors, sensor conditioning and control board and the voltage regulator, and another for the camera. The sensor conditioning and control board contained a 5V reference, which powered the humidity sensor. Figure 2 shows a high-level system design for the payload.

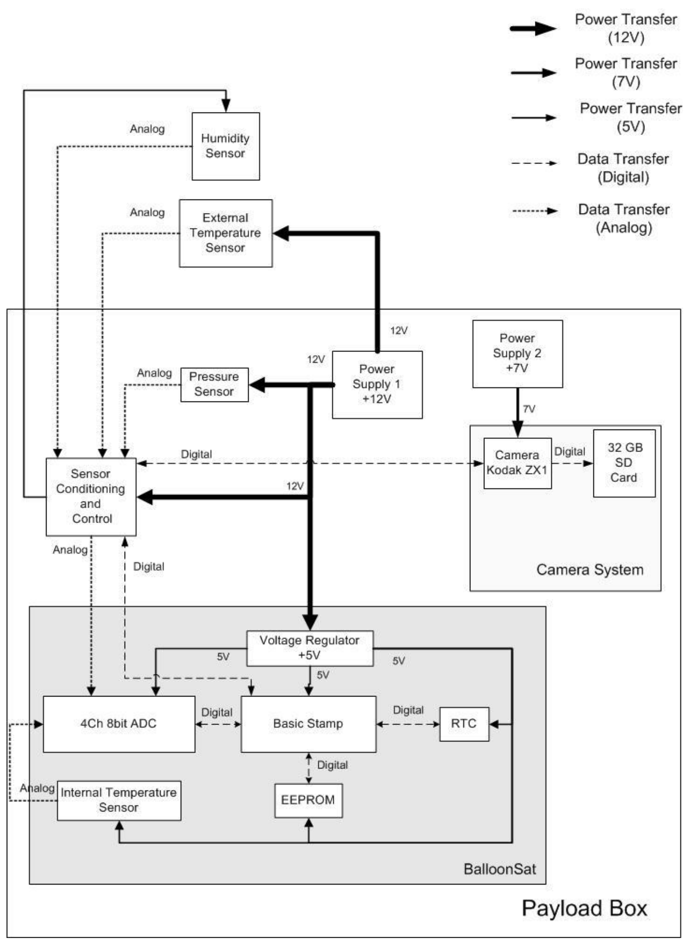


Figure 2: Block Diagram of the PHAT-TACO System

B. Sensors and Power

A temperature sensor attached to the BalloonSat measured the internal temperature of the payload. A 1N457, a small signal p-n junction diode, measured the external temperature of the payload.[7] The forward bias voltage varies linearly with temperature, due to the diode's temperature coefficient.[8] This sensor consumes little power and can operate linearly for temperatures of -65 to 200 ºC.[7]

The model 1230 series pressure sensors are a set of sensors made by Measurement Specialties. This series measures different ranges of pressures from 2 to 100 psi. Since we expected the payload to experience a maximum of 1 atm (14.7 psi), we used a 15 psi absolute pressure sensor from this series. These resistors are composed of piezoresistors arranged in a Wheatstone bridge, and the difference in the output voltages from the bridge relates to the pressure. These sensors have circuitry to compensate for the temperature effect on the piezoresistors, since temperature can range from -20 to 85 ºC. These sensors also contain an internal resistor used to set the gain of the external conditioning circuitry.[9]

The HIH-4000 sensor measures Relative Humidity (RH). The RH sensor uses a capacitive sensing element with on-chip integrated signal conditioning to output a voltage that varies linearly with RH. The sensing element's construction provides resistance to most hazardous conditions. These sensors operate between 4 and 5.8 V with a maximum current of approximately 0.5 mA.[10]

A Kodak Zx1 pocket video, complimentary metal-oxide-semiconductor (CMOS) camera recorded video of the flight with its 4.1 mm lens. The internal memory of the device is 128 MB but has an expansion slot for an SD card. The camera requires 1.5 W of power. This device can take 720p video at 60 fps (frames per second) or 30 fps. This camera is small in size and mass, with a weight of 90 g and dimensions of 2.0 × 4.2 × 0.8 in.[11]

Since the camera drained a large amount of current compared to the other components, two different power supplies were necessary. Power Supply 1 powered all of the sensors, control circuitry, and the BalloonSat. Power Supply 2 supplied power to the camera. We chose lithium ion batteries because of their high capacities compared with other batteries. Using a de-rating factor of 0.75 for 0ºC, the capacity for Energizer Lithium AAA batteries is 900 mA-hrs and is 2250 mA-hrs for AA size batteries. For risk avoidance purposes, eight AAA batteries were used for power supply 1 and four AA batteries were used for power supply 2. With the requirements mentioned in the power budget (Tables 1 and 2) AAA batteries can run Power Supply 1 for ~30 hours and AA batteries can run Power Supply 2 for ~10 hours.

Table 1: Power Budget for Power Supply 1

Power Supply 1					
Component	**Current (mA)**	**Voltage (V)**	**Power (mW)**	**Flight Time (hrs)**	**Capacity (mA-hrs)**
Temperature Interface	1.2	12	14.4	4	4.8
Pressure Interface	2.1	12	25.2	4	8.4
Humidity Interface	0.5	12	6	4	2
BalloonSat	52	12	624	4	208
Total	55.8	-	-	4	223.2

Table 2: Power Budget for Power Supply 2

Power Supply 2					
Component	**Current (mA)**	**Voltage (V)**	**Power (mW)**	**Flight Time (hrs)**	**Capacity (mA-hrs)**
Camera	220	7	1540	4	880

C. Software

The pre-flight software set the real time clock (RTC), cleared all memory locations, and then set the first two memory locations. The timestamp must be accurate in order to correlate time and altitude from the LaACES GPS beacons. After the software set the RTC, the number 2 was stored in the first memory location of the EEPROM. The first two bytes stored the address of the last saved memory location. These two memory bytes tell the BalloonSat where to begin writing data. This allows the flight software to begin writing in the correct memory location upon startup. One risk during flight was a temporary power outage which could reset the BalloonSat. Saving the address of the last memory location written to the EEPROM prevented the software from overwriting data.

The in-flight software recorded measurements of the atmosphere once every six seconds, ensured that the camera recorded video and restarted the video once every ten minutes. The main section of the program looped until the EEPROM was full of data. Using the RTC, the in-flight program checked if six seconds had passed since the last data point recorded. After six seconds, the program saved the timestamp, the data from each sensor, and a "camera status" byte. The camera status byte stored whether or not the camera was recording and whether it is on or off, to verify camera performance afterwards. The in-flight software also controlled the video camera, checking if the camera record light was on. If the light was off, the program attempted to start recording again. Finally, after 100 iterations of data acquisition, the video stopped and restarted.

D. Thermal

The payload flew for approximately four hours reaching an altitude of about 30.5 km. During flight, the payload survived temperatures ranging from approximately -70 to 30 °C. The sensors in the payload needed to be able to operate properly in these extreme conditions. Based on information gathered from a component's data sheet, its maximum and minimum operational temperatures determined its thermal operating range as shown in Table 3.

Table 3: BalloonSat Component Thermal Ranges

Device	Upper Temperature (°C)	Lower Temperature (°C)
ADC, RTC, BASIC Stamp, EEPROM	85	-40
Pressure Sensor	85	-20
Humidity Sensor	85	-40
Temperature Sensor	200	-65
Camera	100	-40
Energizer Lithium Batteries (AA, AAA)	60	-40

Initial thermal calculations, using the LaACES Thermal Flight spreadsheet,[12] predicted that the equilibrium temperature of the interior of the payload at maximum altitude would be approximately 16.0 °C and the coldest temperature, at approximately 10 km altitude, would be 15.8 °C. These temperatures are well within the operating ranges of the components.

E. Mechanical

The mass budget for this project was 500 g. Table 4 shows the measured mass of each component.

Table 4: Mass Budget

Component	Mass (g)	Uncertainty (+/-g)
BalloonSat	66.3	0.05
Power Supply 1	71.8	0.05
Power Supply 2	63.7	0.05
Signal Conditioning Board and sensors	101.5	0.05
Foam Structure	99.6	0.05
Camera	97.8	0.05
Total	500.7	0.12

The payload box, constructed of blue insulation foam and wrapped in aluminized mylar, was the shape of a regular hexagonal cylinder (Fig. 3). It had a bottom glued in place and a lid secured by duct tape. The box had two holes 17 cm apart to run through the height of the payload structure to allow for strings that attach to the balloon vehicle. The lid had ne hole for the camera to take video. The payload was 17.5 cm in height including both the bottom and the lid. There was an external sensor cover to house the humidity sensor in order to protect it from direct sunlight.

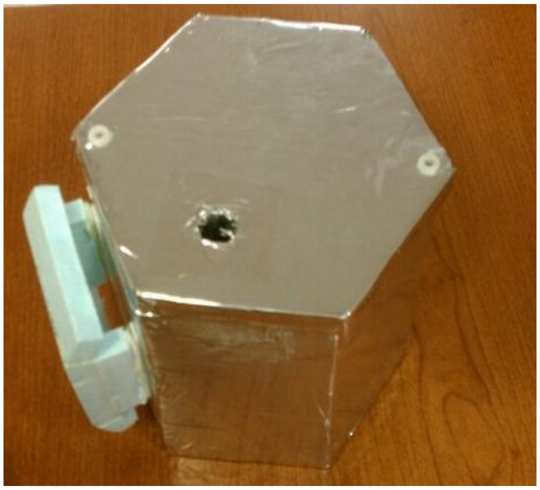


Figure 3: The finished payload box

The internal structure of the payload included the BalloonSat with sensors, the power supplies, the signal conditioning board and the camera. A foam insert measuring 15.5 cm by 14 cm secured the BalloonSat with the signal conditioning board and the pressure and internal temperature sensors, battery packs, and camera inside the payload. One side of the insert contained the BalloonSat, sensors, and signal conditioning board and the other side of the insert housed both battery packs and the camera for the most even weight distribution. A rectangular cut out secured the BalloonSat and the signal and conditioning boards and the battery packs were fastened with Velcro. The camera sat on a foam shelf secured

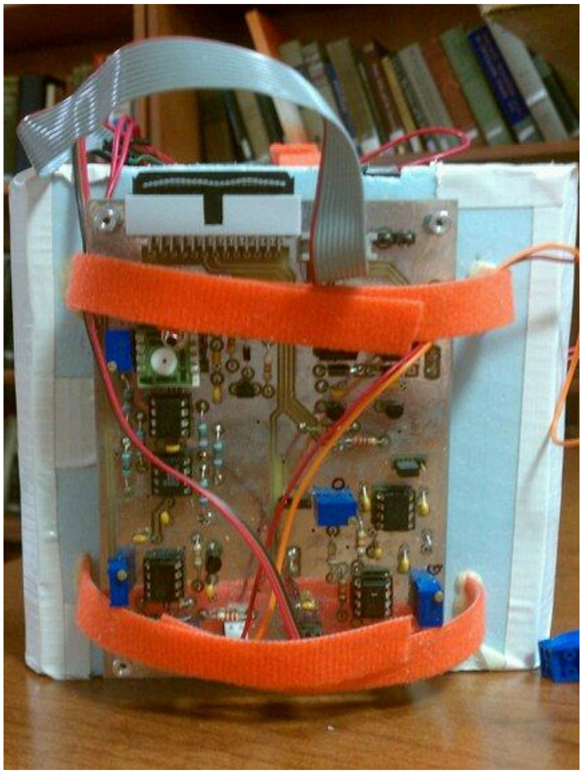
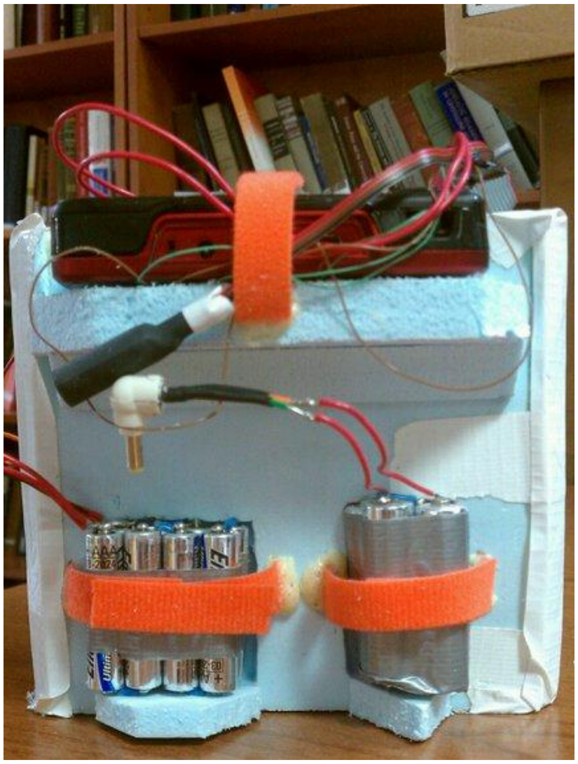



Figure 4: The two sides of the finished internal structure

by Velcro. There was enough room between the walls and the insert to allow the battery pack to make a connection to the BalloonSat and signal conditioning board on the other side. The external temperature and humidity sensors fit under the lid in order to take external readings. Fig. 4 shows the two sides of the final internal structure.

F. Fabrication and Integration

The payload box was constructed first. Work then began on the electrical and software components of the payload. Our team prototyped each of the temperature, pressure and humidity sensors separately on a solderless breadboard once the sensor became available. Next the sensors were interfaced to the BalloonSat. The software was written and tested until it ran and printed data successfully. Then the software was loaded into the EEPROM of the BalloonSat, and the software and electronic integration was tested. Finally, the electronics with loaded software was integrated into the payload box to move onto system testing.

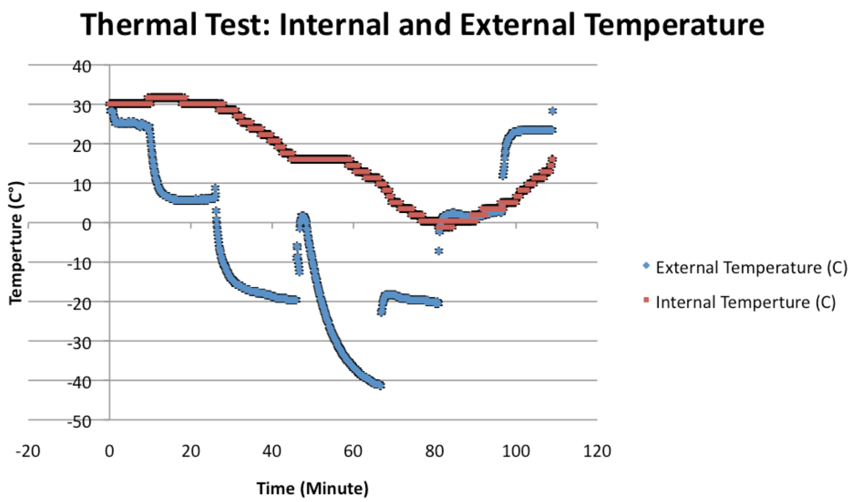


Figure 5: Thermal Test Results: Internal temperature in red, External in blue.

G. System Testing

In order to verify proper securing of all subsystems and to ensure that they could withstand the forces involved with a balloon flight, the completed payload was shock tested. With the lid taped down, the payload was dropped from a height of 10 feet with the two external sensors inside the payload to protect them. No shifting occurred; the components were intact; and the data collected was consistent with the expected conditions.

In order to verify that all subsystems could survive the thermal conditions of flight, the payload underwent a thermal test. The powered payload was exposed to various temperature environments. The environments included the LaACES lab for 10 minutes at approximately 20 °C, a refrigerator for 15 minutes at approximately 0 °C, a freezer for 20 minutes at approximately -20 °C, and then a dry ice cooled environment for 20 minutes at approximately -70 °C.[6] Then the payload was returned to the freezer for 15 minutes, the refrigerator for 15 minutes, and finally the LaACES lab for 10 minutes. When downloaded and analyzed, the data showed that all systems performed as expected. The pressure readings were a steady 1 atm throughout the test. The humidity results changed suddenly when the payload changed environments. As can be seen in Fig. 5, the external temperature readings jump between temperatures since the payload changed directly from one environment to another. The internal temperature shows a more gradual change due to the electronics and insulation. The lowest temperature reading is lower than our calculations, due to the fact that the calculations were steady state calculations and the payload didn't reach a steady state.

In order to verify that the payload could withstand low-pressure conditions, a vacuum test was performed. To simulate the ascent, the pressure inside the chamber was decreased in 15 mmHg increments each minute until reaching 80 mmHg. Then the pressure was decreased in 3 mmHg increments each minute. Once the chamber reached a pressure of 6 mmHg, the process was reversed to simulate the descent of the payload. Downloading and analyzing the data showed that all systems performed as expected.

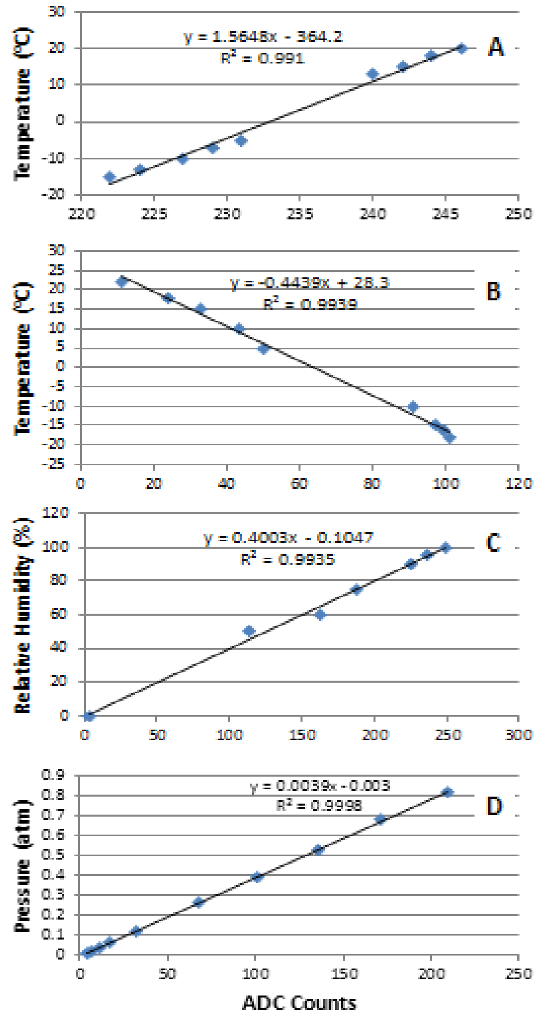


Figure 6: Calibrations vs. ADC Counts for: (A) Internal Temperature, (B) External Temperature, (C) Humidity, (D) Pressure

H. Calibrations

Fig. 6 shows the calibration results for all four sensors. For the temperature sensor, a PASCO SF-9616 multimeter was used to measure the temperature in various environments. The sensors were exposed to room temperature, then placed in a refrigerator and then placed in the freezer. The SF-9616 value and corresponding ADC for each environment were recorded and then input into an Excel spreadsheet. The correlation between the ADC values and the temperature was calculated.

The humidity sensor and a Hobo humidity sensor were placed in a saturated environment, a NaCl humidity reduced environment, and an outside environment. The recorded values were used to calculate a line of best fit between the Hobo's detected humidity and the ADC values recorded from the humidity sensor.

A vacuum chamber was used to calibrate pressure. First, the pressure sensor measured ground-level pressure; The variable resistor on the payload was adjusted to set ground-level pressure near the top of the 3V range. The vacuum chamber stopped at various intervals, the pressure sensor took several readings at that pressure, and the pressure indicated by the vacuum chamber pressure gauge was recorded. The data points were plotted to create a line of best fit for the pressure sensor's output voltage versus absolute pressure.

IV. Results

The post flight software displayed the data delimited by commas. Term232, a Windows 32 terminal emulator program, was employed to import the data output to a plain text file. From this file, the data were put into Microsoft Excel. Excel performed the conversion from raw ADC counts to percent relative humidity, temperature, and pressure based on the calibration data. A program written in C++ calculated the radius of the balloon from x and y measurements. This program works by looping through every possible x,y combination and calculating the radius at each point, then calculating the standard deviation of the radius measurements at each point. A minimum in the standard deviation indicates the radius. In addition, the video was analyzed by eye to determine and record when the payload passed through a cloud.

One problem encountered was that for the first 35 minutes on the launch pad no data were saved to the EEPROM. Then three minutes into the flight, the payload seemed to regain the ability to write data to the EEPROM. This same problem also happened to two other payloads, suggesting there was an external source of interference on the launch pad that caused this problem. No problems of this nature have arisen in previous launches from the exact same area. An alternate explanation of this problem is that the payloads were all using very similar software that caused the exact same error.

Both the internal and external temperatures from the flight data followed the expected trends. The external temperature readings (Fig. 7B) resemble the NOAA data presented in the introduction, and the internal readings resemble the internal temperature testing performed before flight (Fig. 7A, ascent in green; descent in blue). From this data, it was determined that the Tropopause extended from 13.6 to 18 km on the day of the flight.

The humidity results also follow the same general trend but contained three peaks (Fig. 7C, ascent in red; descent in blue). The payload passed through two clouds on the ascent from 1.02 to 1.14 km and the other from 1.18 to 1.23 km and one from 0.86 to 0.66 km on the descent. The first cloud on the ascent was during the time-period when the payload didn't collect any data. The second cloud the payload passed through shows a corresponding value of 80% on the humidity data. The third time the payload passed through a cloud there is a corresponding value of 100% on the humidity data. When the humidity was highest, the temperature readings deviated the most from the standard atmosphere.

The balloon radius expanded as expected for a Kaymont 3000 g sounding balloon. The final diameter reached approximately 11 m which is consistent with the cut-down altitude. Fig. 8 shows the calculated balloon radius throughout the flight, while Fig. 9 shows screenshots of the balloon just after launch and just before cut-down.

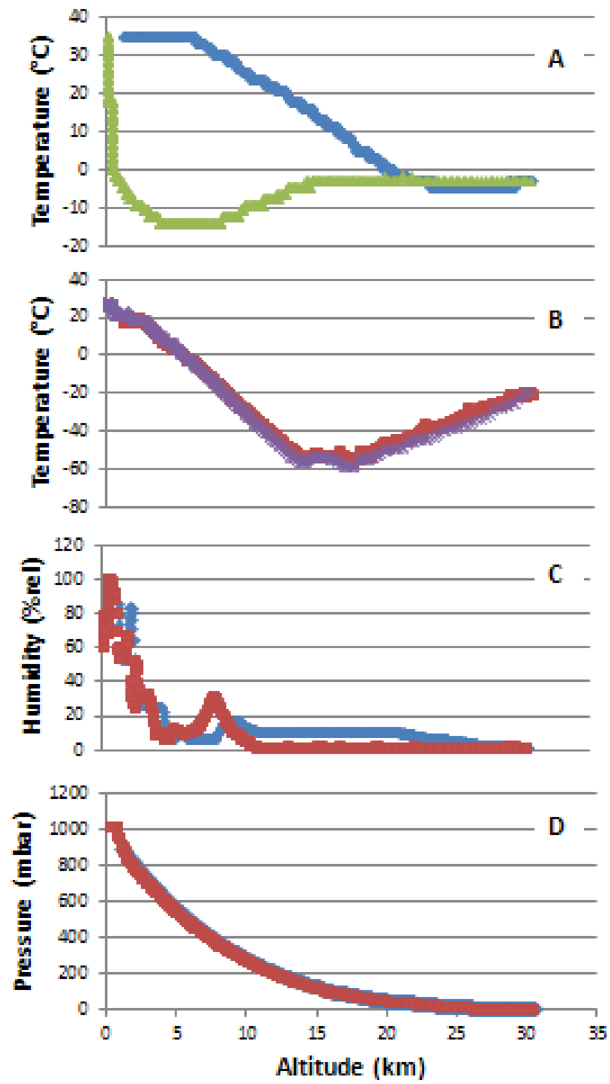


Figure 7: Results vs. Altitude
(A) Internal Temperature (C) Humidity
(B) External Temperature (D) Pressure

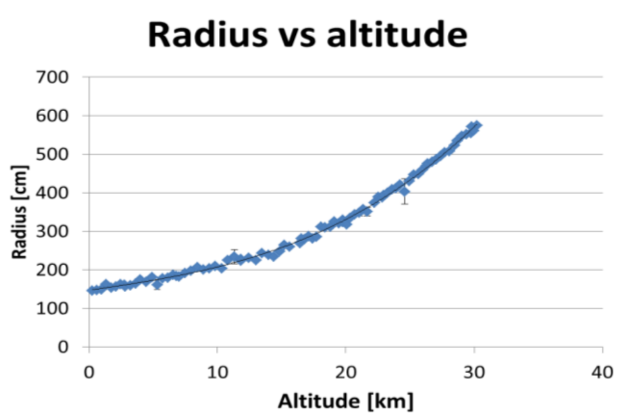
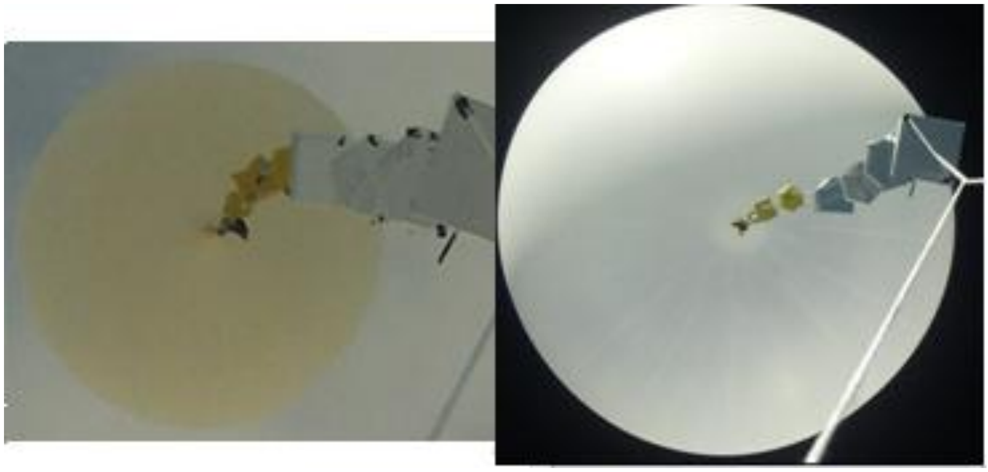


Figure 8: Balloon Radius vs. Altitude



V. **Figure 9**: Balloon Radius after launch (left) and before cut-down (right).

Summary

The LaACES program successfully introduced the PHAT-TACO team of undergraduate students to the concepts, skills and processes inherent in the aerospace industry. Students completed a semester-long educational program that provided the knowledge necessary to design, construct and launch a payload to an altitude of approximately 100,000 feet above the surface of the Earth. The experiment measured and recorded temperature, pressure and humidity as well as video, beginning three minutes after launch through vehicle and payload recovery. An unexpected error was encountered which prevented data from being recorded while the payload waited on the launch pad, but the issue resolved itself shortly after launch. Changes in humidity were correlated with the payload's passage through clouds, and the measured temperature and pressure values generally followed the expected trends. This experience provided the team with the opportunity to not only increase knowledge and comprehension of the atmosphere, but also to complete, and document, a hands-on project that resulted in achieving the mission goal.

VI. Acknowledgments

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