Measuring and Calculating the Speed of Sound Profile during a Total Solar Eclipse using LaACES Balloon

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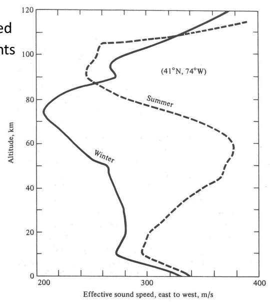
Abstract

The goal of this mission was to test the speed of sound at different altitudes and ultimately at a maximum height of 100,000 feet during a total solar eclipse. In conjunction with this testing, environmental parameters including temperature, pressure, and humidity are measured and used to calculate the speed of sound to compare to the measured results. The first balloon launch of payload Dorothy was conducted in NASA CSBF on May 16, 2017. The improved payload "Dorothy 2" was launched successfully in Carbondale, IL. on Aug. 21, 2017. Data are analyzed and further improvement plan is discussed.

Background

The measurements of speed of sound profiles were conducted in the 1960's when measurements were conducted in New York City, New York, both in the Summer and Winter seasons, as show in the figure to the right [1]. The measurements were in a much wider range (0 to 120 km). For the altitude range of 0 to 30 km, it can be seen in the figure that the speed of sound decreases as it reaches 10 km and then increases again as it reaches the 30 km altitude.



The speed of sound can be calculated using measured temperature, humidity, and pressure data from an empirical formula studied by E.A. Dean

$$c = 20.06\sqrt{T_s} \qquad (1)$$

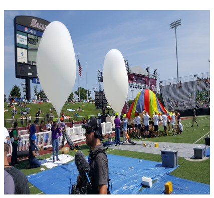
where T_s is called absolute sonic temperature that includes the effects of humidity and pressure [2]. The speed of sound on a normal day is roughly 340 m/s under one standard atmospheric pressure on the surface of the earth.

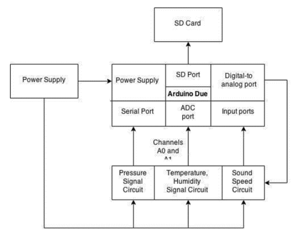
The physical measurement of the speed of sound can be done by timing how long a sound wave reaches a target of a fixed distance. In the balloon payload Dorothy, the speed of sound is measured by timing a ultrasonic sonar pulse reflecting off a purely reflective mirror. In the meantime, temperature, pressure, and humidity are measured and applied to the empirical formula (1) to calculate the speed of sound. The measured and calculated results are compared.

Payload Design

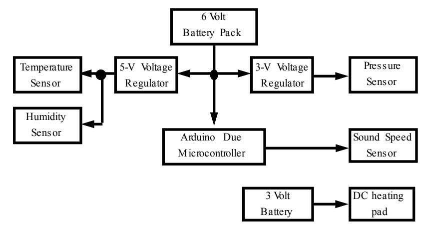
Electrical Design

The payload needs to be able to conduct all environmental testing as well as measuring the time from the ultrasonic sonar module. To do this without losing resolution in the data and not receiving false readouts from the sonar module itself, an Arduino Due is used. Such a microcontroller has a clock speed of 87 MHz which can read the timing of the sonar down to the microsecond level and can read the data from all available components in a timely manner or around 3.14 seconds a reading.





Overall layout of electronic components



Power supply layout

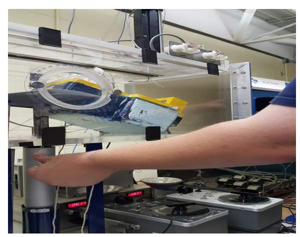
The Arduino Due allows for a lower power consumption and better compatibility with existing hardware to make the integration seamless.

A 6-V battery pack supplies power for the microcontroller and sensors. Most of the devices run off 3.3 V line while the sonar runs off the 5 V line supplied by the board. Most of the hardware connections are actually done through the coding of the Arduino Due, which lightens the payload while also makes it easier to test and prepare the module before flight. To ensure the sonar sensor still functions at low temperatures, a heading pad is used. The heading pad, constructed using a mesh of polyester filament and micro metal conductive Fiber, is powered by a stand-alone 3-V battery.

Mechanical Design

The external structure is composed of two layers of 1/2 inch thick polystyrene. The dimensions of the container form a box with sides 7.5 inches wide, 8.8 inches long, and 4.69 inches tall (19.05 cm x 22.38 cm x 11.91 cm). The thickness of the box serves as thermal insulation and shock absorption. Econokote, a heat shrinking skin, was ironed on to the outside of the box for extra structural and thermal support. There are 5 holes in the box. Two holes are 16 cm apart at opposite corners of the box on top and bottom for the strings, with another one on top for external temperature sensor, pressure sensor, and sonar. The circuit boards were glued to the bottom of the box with hot glue using a piece of foam as a spacer. The housing was built to be compact to save weight and to heat components and batteries more efficiently. Small PVC pipes, which are stronger than ordinary soda straws, were used to help guide the rope and make it easier to open and close the module. The parts for holding the mirror and sonar are 3D printed using PLA plastic, known for it's durability and ease of use. All parts are glued using Gorilla brand glues due to their high strength.

Completed build of Dorothy 2 module



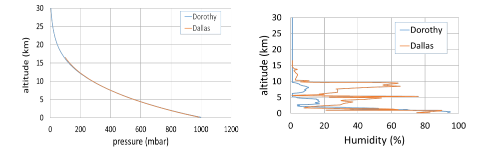
Wind Tunnel testing of Dorothy 2

Software Design

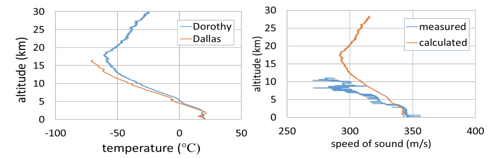
The software runs off a main loop that runs infinitely. An interrupt was designed to allow for safe system initiation and shutoff and also safe data acquisition in the form of an SD card. The program records the data from all sensors within 3.14 seconds. Another loop within the main loop takes about 10 readings from the sonar in around 3 seconds to give an average reading in the post flight analysis. The program also has an initial startup check sequence and LED notification located on the Arduino shield for visible notification to the operator.

Results

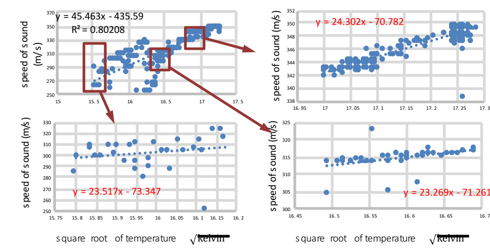
The environmental data measured in the launch at NASA CSBF on May 16 agree reasonably well with the data measured by Dallas weather station which is about 122 miles north from the CSBF. The sonar stopped working at temperatures lower than -40 °C (readings are all zeros). In addition, the acquired speed of sound data are quite noisy.



Pressure and humidity data from May 16th launch

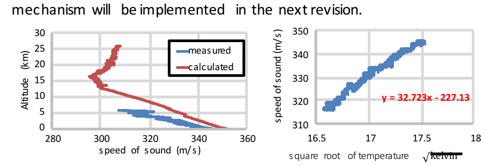


Temperature data and speed of sound plotted as measured and calculated from May 16th launch



Sonar data from May 16th launch

In the second launch, the sonar was functioning over the entire flight. Data are much less noisy. It means the heater worked as expected. However, the recorded ping times at altitudes higher than 5 km are significantly less than reasonable values. Further investigations excluded the wind or vacuum influences. Similar behavior was repeated in freezer tests as frost was observed on the transmitter/receiver. So a defrosting mechanism will be implemented in the next revision.



Sonar data from Aug. 21st launch during solar eclipse

Conclusion

The results from the Aug. 21st were as expected for the conditions that had taken place during the eclipse. Environmental readings showed improved reliability in its data compared to the first launch. The sonar experienced icing on the transmitter/receiver causing the data to give false readings. Overall, the launch was a success and the data can be used to in conjunction with future launches.

References

1. Yang, X.R. *Atmospheric Acoustics*, De Gruyter (2016)
2. Dean, E.A. *Atmospheric Effects on the Speed of Sound*, U.S. Army Report ASL-CR-79-1011-4 (1979)