SkeeterSat Calibration Report

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Introduction:

The SkeeterSat is a basic electronic system designed to take the input of both temperature and light intensity and produce a corresponding audio output, in the form of beeps. It was developed by LaACES based on CricketSat, which was a radio device that originated from Stanford University's Space Science Development Laboratory. CricketSat was created by professor Bob Twiggs in the spirit of past amateur radio projects that had focused on the measurement of temperatures in space using changing radio signals. In general, the goal of CricketSat was to introduce students to basic telemetry, and the SkeeterSat is very similar in this regard.

The SkeeterSat is built on a circuit board and powered by a 9-volt battery. The temperature input is taken by a RL0503-5820-97-MS thermistor (a resistor that changes its resistance with temperature differences) and the light intensity is measured by a photoresistor (resistor that changes resistance with light intensity). For this experiment, only the thermistor was used.

The two different inputs are interpreted and converted to audio output by a collection of other resistors and capacitors in the device, as well as a TLC556 timer. The schematic for the SkeeterSat is shown as **Figure 2** on page 2.

The beeps produced by the device's speaker will speed up or slow down based on the light intensity (less light = increased gaps between beeps) and will change pitch based on the temperature (higher temperature = high pitch of beeps). This beeping data can be interpreted using a software called spectrogram, which measures the frequency (in hertz) of audio inputs and displays them visually as a function of time.

Objectives:

The goal of the calibration is to ensure that the SkeeterSat is accurate at predicting temperature based on the fundamental frequency of its beeps.

Materials:

- 500mL beaker with water
- Thermolyne Cimarec 3 Hot Plate
- Heat resistant gloves
- Pasco scientific digital meter (model SF-9616) (set to "thermometer" and set to the "<200 °C" mode)
- Assembled SkeeterSat

- 9-volt battery
- Spectrogram Software (access from LaACES website)
  - Must be downloaded on a device with a microphone or a device connectable to a microphone. In this case, an HP laptop model 15-da0xxx was used, along with its built-in microphone.
- Ice (small enough chunks to fit into beaker)
- Calculator
- Lab notebook and pen

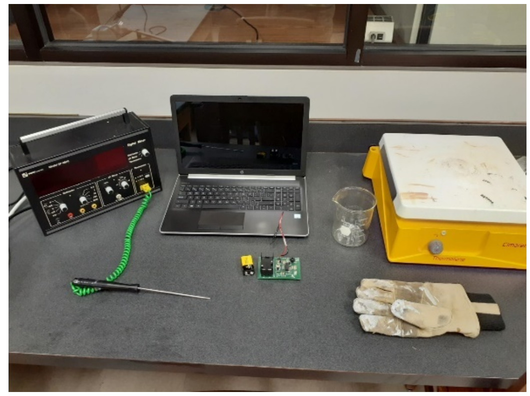
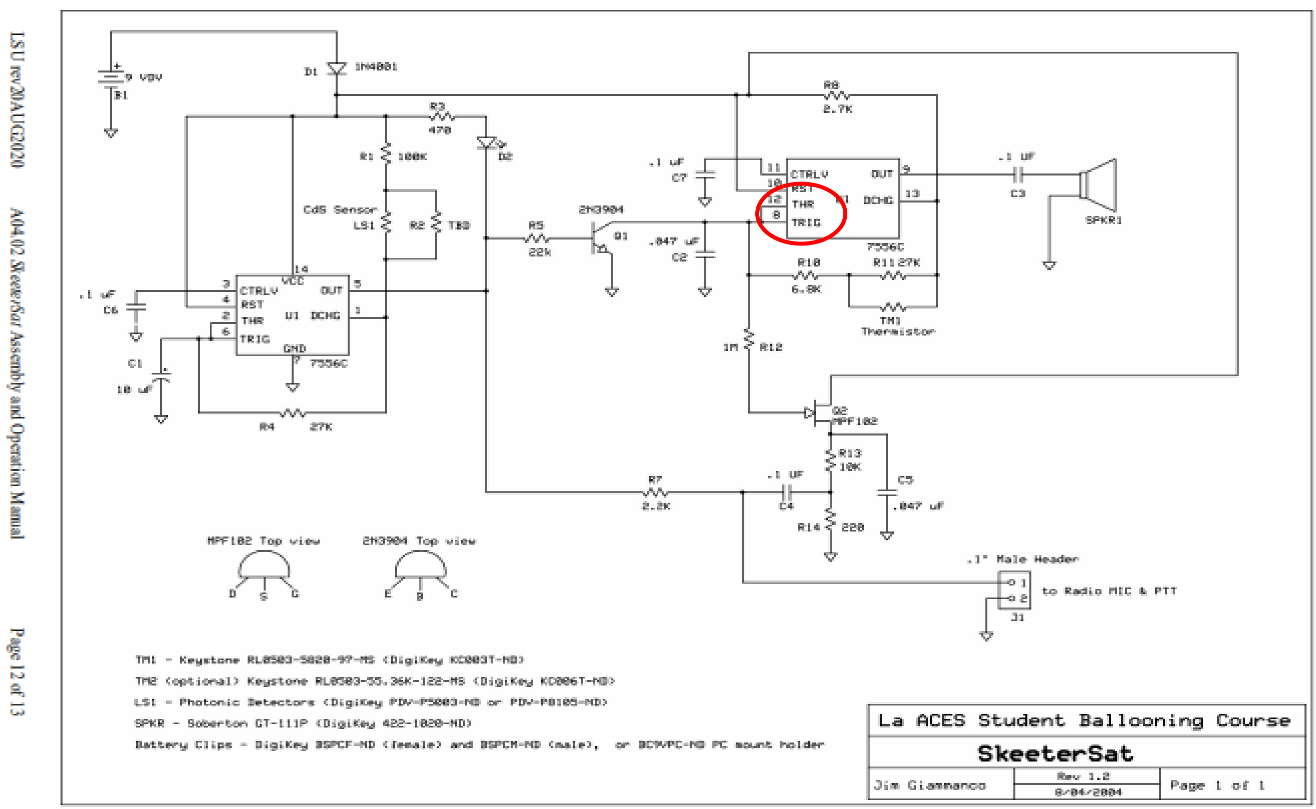


Figure 1 (above): This is a photo of the lab setup used. On the left is the thermometer, and on the right is the hotplate used to heat the water. The laptop in the center was used to run spectrogram and record the audio data, and just below it the SkeeterSat is visible.

Figure 2 (below): The SkeeterSat was assembled according to this schematic, where the various components and connections in the device are depicted. The left side of the schematic mainly shows the photoresistor and the parts of the SkeeterSat that connect to it. This calibration report mainly pertains to the upper right side, where the thermistor connects to its respective timer; the output of this timer is related to the resistance provided to the trigger pin (in red). This schematic is useful in calculating this exact relationship later on.



Calibration Process:

- Step 1: Add 450mL of water to the beaker.
- Step 2: Place the beaker with water in it onto the hot plate.
- Step 3: Set the hotplate to the "10" setting.
- Step 4: While the water is heating, open spectrogram software and adjust to the appropriate settings.
- Step 5: When the water has come to a steady boil, stir the water with the end of the thermometer to ensure even heating. Remove from hotplate.
- Step 6: Keeping thermometer in center of beaker, allow temperature reading to stabilize.
- Step 7: At the same time as step 6, insert the 9-volt battery to the SkeeterSat and place the thermistor into the beaker.
- Step 8: Begin spectrogram software; adjust window settings as needed.
- Step 9: Stop recording with spectrogram as soon as the temperature reading on the thermometer shifts. If the temperature shifts at all while adjusting spectrogram window settings, ensure that the temperature is consistent throughout another entire recording time, and use that recording instead. Record again if the temperature shifts. 5-10 beeps per recording time is sufficient.
- Step 10: Use the visual data to measure fundamental frequencies and record them in the lab notebook- subtract two harmonic frequencies of the same beep that are directly above or below one another. Repeat for 5 beeps, recording as many harmonic frequencies as possible per beep.
    - Originally, step 10 was completed poorly, and not enough data was measured for reliable calculations to be made. To resolve this, the listed procedure was repeated a second time on a different day to gather more data.
- Step 11: As the beaker cools, continue to take frequency and temperature measurements using steps 6-10.
- Step 12: As the cooling process slows, add ice and stir using the thermometer to speed up the process of getting to lower temperatures. Dump excess water out of the beaker to avoid overflow and keep the water level consistent. Repeat steps 6-10 for the lower temperatures.
- Step 13: In an excel sheet, chart the data for each fundamental frequency at each temperature, finding the mean, sample standard deviation, and uncertainty.

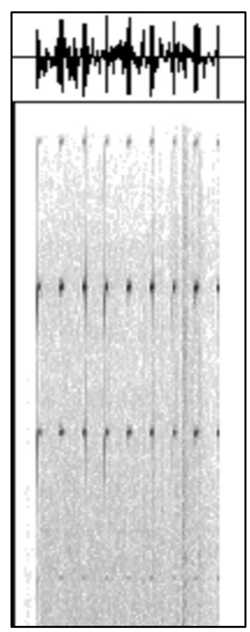


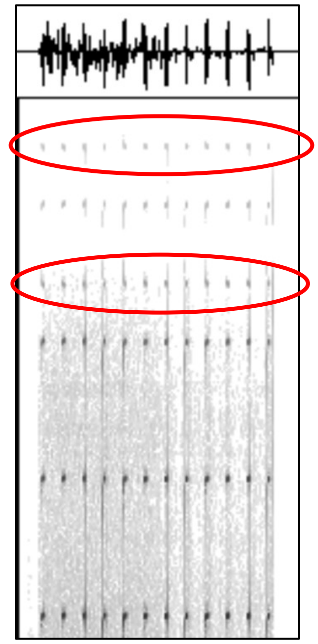
Figure 3 (right): An image of the spectrogram software after recording the SkeeterSat's beeping. Time (ms) is on the x axis while frequency (Hz) is on the y axis. Sometimes the harmonic frequencies were faint and difficult to locate at first, as can be seen with the row near the very bottom of this image.

Calibration Results:

Computing Uncertainties:

Determining the uncertainty in frequency was a difficult aspect of this calibration. For temperature, the manual of the thermometer was used, and it was found that readings are accurate within 0.5% or 0.5°C. In this case, 0.5°C was a larger margin of error, so this was used in order to stay on the cautious side.

Figure 4 (right): At 51.3°C, there was a strange anomaly in the display on Spectrogram; 2 sets of extra dots (circled in red) didn't seem to align with the rest of the harmonic frequencies. The cause of this is unknown, but could be explored further in future experiments



One component of the uncertainty of the fundamental frequencies seen in **Table 1** (page 5) was based on the standard deviation of the mean. This was calculated in **Equation 3**, and required the mean (m) and sample standard deviation (σ) of the data, which were calculated as follows.

Equation 1: This shows the mean fundamental frequency calculation where m is the mean fundamental frequency at a temperature T, $\sum f$ is the sum of all frequency measurements at T, and N is the total number of frequency measurements at T.

$$m = \frac{\sum f}{N}$$

Equation 2: This shows the sample standard deviation (σ) at temperature T, where m is the mean fundamental frequency at temperature T, f is an individual frequency measurement at T, and N is the number of frequency measurements taken at T.

$$\sigma = \sqrt{\frac{\sum(f-m)^2}{N-1}}$$

Equation 3: This shows the standard deviation of the mean (σ_m) for a fundamental frequency at a temperature T, where σ is the sample standard deviation from **Equation 2** and N is the total number of frequency measurements taken at T.

$$\sigma_m = \frac{\sigma}{\sqrt{N}}$$

Apart from the standard deviation of the mean (σ_m), there was also some initial uncertainty in the measurements of the harmonic frequencies themselves, as every measurement taken while the “FFT size” setting was 1024 had an uncertainty of ±22Hz, and every measurement taken while “FFT size” setting was 2048 had an uncertainty of ±11Hz, according to Spectrogram.

Since two of these uncertain measurements were subtracted in order to find each fundamental frequency data point, their uncertainties were added in quadrature to get the uncertainty of each fundamental frequency measurement. This is a systematic error rather than random error (since it was already accounted for by the software), and as such, it should be added to the uncertainty that was calculated from the above formula (which gave us the random error).

This means that in calculating the final uncertainty in the mean for the fundamental frequency, **Equation 3** was first used, and then the systematic error was added on top of that value.

For instance, at 94.4°C, we can refer to **Equation 3** and see that.

$$\sigma_m = \frac{\sigma}{\sqrt{N}} = \frac{112.0569}{\sqrt{13}} = 31.079$$

Then, because the systematic error for each harmonic frequency measurement was ±22 in this case, the systematic error of each fundamental frequency was calculated using quadrature:

$$\sigma = \sqrt{22^2 + 22^2} = 31.113$$

Both errors were then combined with basic addition (in order to account for maximal error) to get the final error that was used, rounding to the nearest whole number.

$$31.113 + 31.079 = 62.192 = 62$$

The results for all calculations are as follows:

Table 1: Average Fundamental Frequency as a Function of Temperature

Temperature (°C) (+/-0.5)	Freq Mean (Hz)	Number of measurements taken
94.4	1789±62	13
81.3	1689±44	10
70.4	1585±24	5
62.9	1537±22	10
51.3	1402±19	10
32	1126±20	10
13.8	837±19	15
1.2	673±19	15

Theoretical vs. Experimental Results:

The theoretical results were calculated by using the formula found on page 10 of the integrated circuit/TLC556 timer data sheet. It gives **Equation 5**.

Equation 5: period of the TLC556 timer with regards to capacitance (C_t), resistance A (R_a) and resistance B (R_b). See page 10 of the TLC556 data sheet for a diagram that indicates the exact meaning of these values.

$$\text{Period} \approx C_t(R_a + 2R_b)(\ln 2)$$

Comparing the visual on page 10 of the TLC556 timer data sheet with upper ride side of the SkeeterSat schematic, the following values can be found:

$$C_t = 0.047\mu f$$
$$R_a = 2700\Omega$$

Equation 6: Using the basic laws of adding resistances in series and in parallel, and referring to the schematic, it can be seen that:

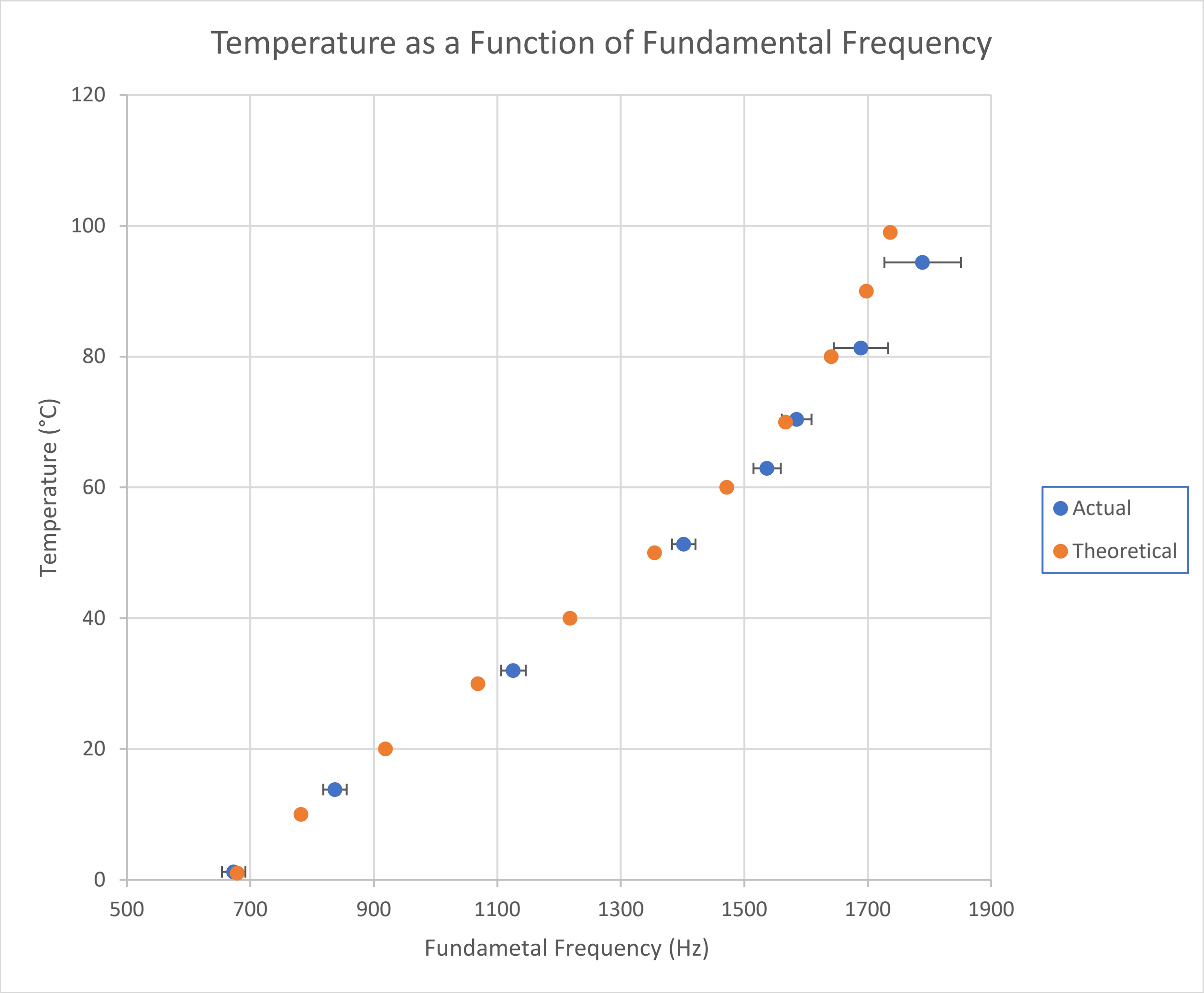
$$R_b = 6800\Omega + \left(\frac{1}{27000\Omega} + \frac{1}{R_T}\right)^{-1}$$

where R_T is the resistance of the thermistor at any given temperature T. To find R_T, the data sheet of the RL0503-5820-97-MS thermistor was consulted, along with page 69 of the thermistor temperature vs. resistance curves pdf document. Using that information, the resistance at a given temperature T was found to be given by **Equation 7**.

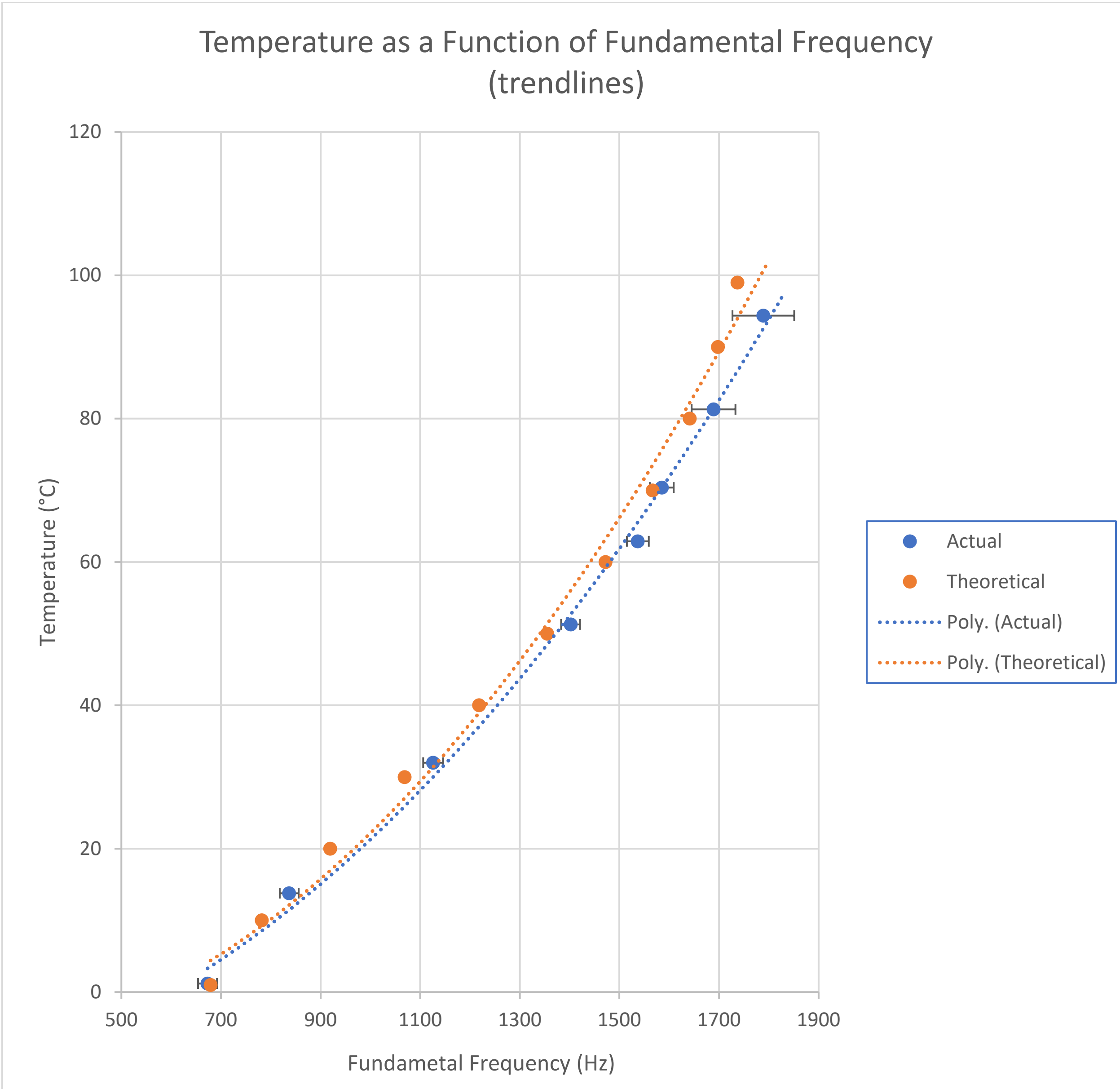
Equation 7: Resistance of the thermistor (R_T) at temperature T

$$R_T = \left(\frac{R_T}{R_{25}}\right) 10\,000\Omega$$

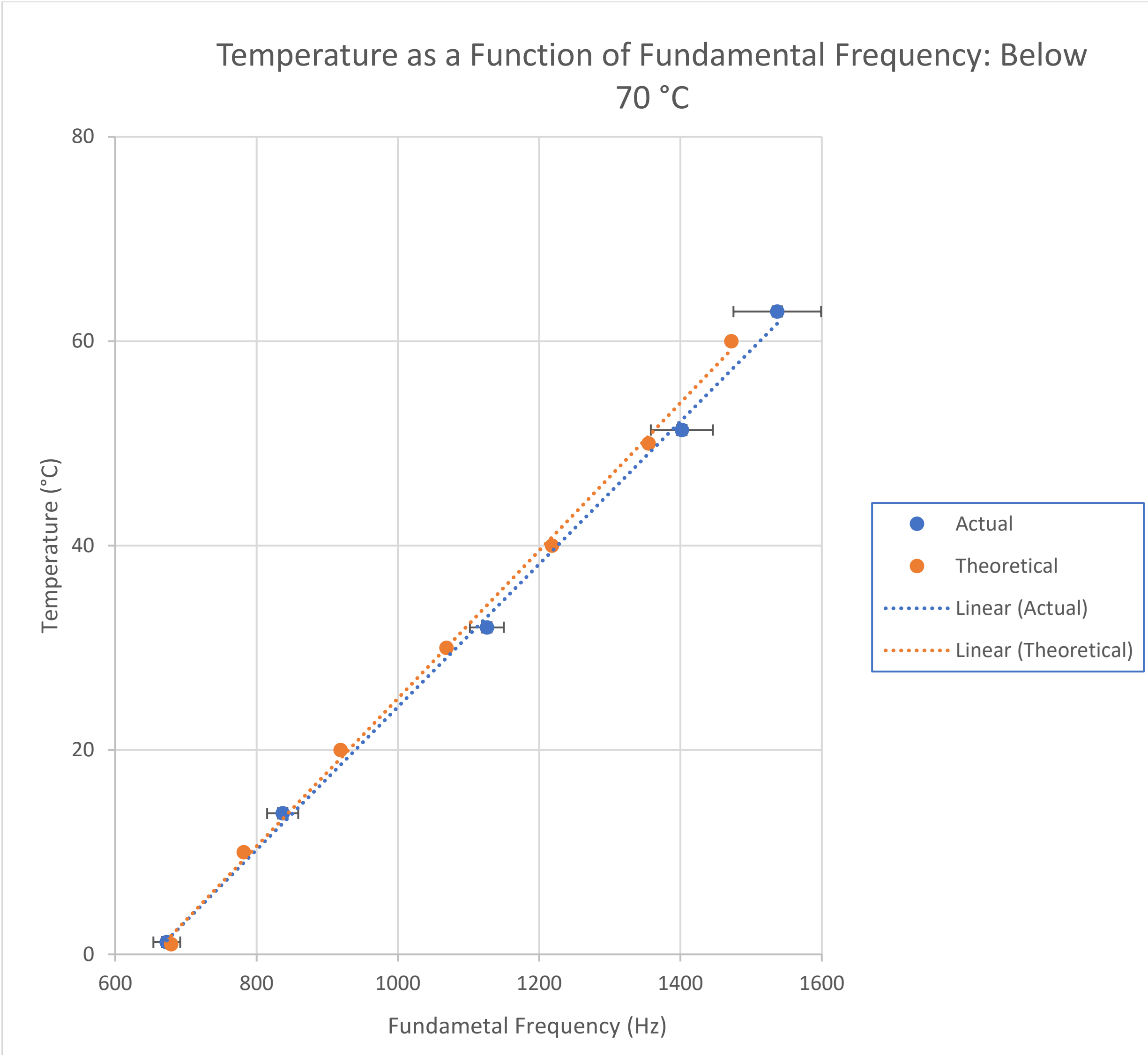
where $\frac{R_t}{R_{25}}$ is the ratio of the resistance at temperature T to the resistance at T = 25°C (this $\frac{R_t}{R_{25}}$ value is found for various temperatures on the Thermistor Temperature vs. Resistance Curves pdf). Thus, this was used to solve for R_b at various temperatures, and R_b was consequently used to find the value of the frequency of the SkeeterSat beeps at various temperatures. These values were plotted on the same graph as the experimental results in order to compare the two, as seen on the page below. The results ended up being very similar with the error margins.



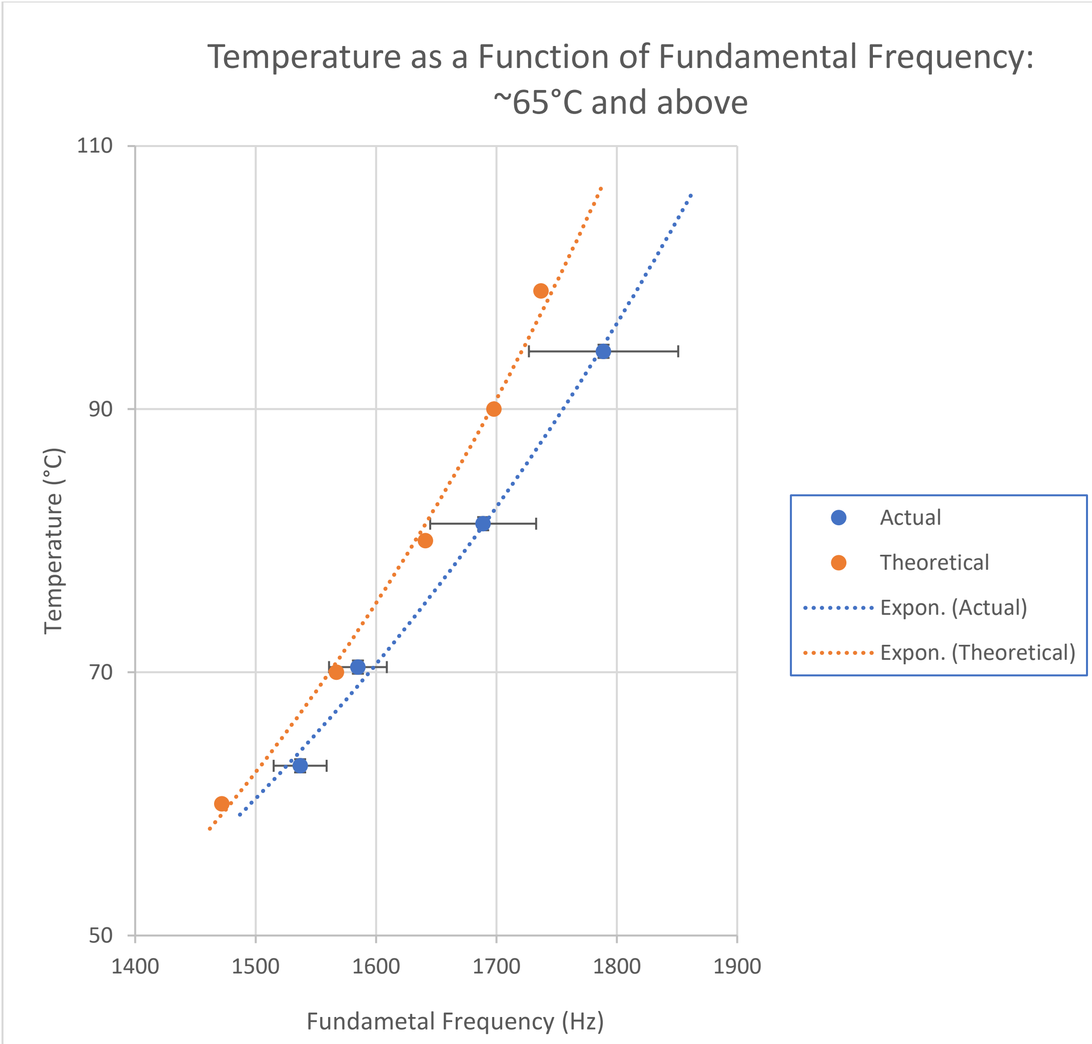
Graph 1 (above): Theoretical vs. Actual Data Points with no trendline. Note: temperature (y-axis) error bars were included but were too small to be seen. Without any trendlines, it appears that the trend is linear before beginning to increase exponentially at around 1500Hz.



Graph 2 (above): Theoretical vs. Actual Data Points, depicted with the trendlines as 2nd degree polynomials. The actual results gave the function, T = (3*10^-5)f^2 + (0.0019)f - 12.367, while the theoretical results gave the function T = (4*10^-5)f^2 – (0.0112)f - 6.276.



Graph 3 (above): Because it didn't seem accurate to express the trend in terms of a polynomial (because the trend seems to switch from linear to exponential at 1500Hz), only the points where the temperature was below 65°C were used in this graph. A linear trendline was found within this window. This way, when analyzing frequencies in the range of 600-1500Hz, the equation representing this linear trendline will be used in order to find temperature, and it will be more accurate than using the 2nd degree polynomial from **Graph 2**. The actual results measured this linear equation to be T = 0.0699f - 45.656.



Graph 4 (above): This graph is likely not as accurate given the smaller range of data available for the higher temperatures, but it tries to isolate the exponential curve for temperatures starting at 62.9°C and higher, because the data after this temperature clearly starts to convey an exponential trend. The equation of the actual results for this graph was $T = 5.7964e^{0.0016f}$, and it can be used when trying to find temperatures using frequencies above 1500Hz.

Conclusion:

Overall, the calibration seemed to be a success, as the expected theoretical outcome was closely matched by the experimental data. Using the formulas discussed with the graphs, it is now possible to find the temperature of the thermistor of the SkeeterSat based on the frequency of its beeps emitted.

Some possible future investigation could be spent finding more information about the source/behavior of the anomaly displayed by Spectrogram in **Figure 4**. In trying to recreate that display, it may be possible to find out more about whether it was caused by an issue with the microphone, the SkeeterSat itself, or some other outside variable; this would allow for a better understanding of which conditions the SkeeterSat functions best in.

Resources:

TLC556M Datasheet- Texas Instruments. 2017, laspace.lsu.edu/laaces/wp content/uploads/2020/09/R05.04_tlc556m_datasheet.pdf.

NTC Type MS Thermometrics Epoxy Coated Thermistor. 2014, laspace.lsu.edu/laaces/wp-content/uploads/2020/09/R05.05_NTC_Type_Thermistor_Datasheet.pdf.

Sensor Temperature Resistance Curves. Nov. 2014, laspace.lsu.edu/laaces/wp content/uploads/2020/09/R05.06_Thermistor_TvsR_curves.pdf.