Skin Color-Corrected Pulse Oximetry

Joel Kelsey, Max Melendez, Clarissa Pavao, Jack Roberts

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The Team

Joel Kelsey

- Software
- Hardware

Max Melendez

- Theory!

Clarissa Pavao

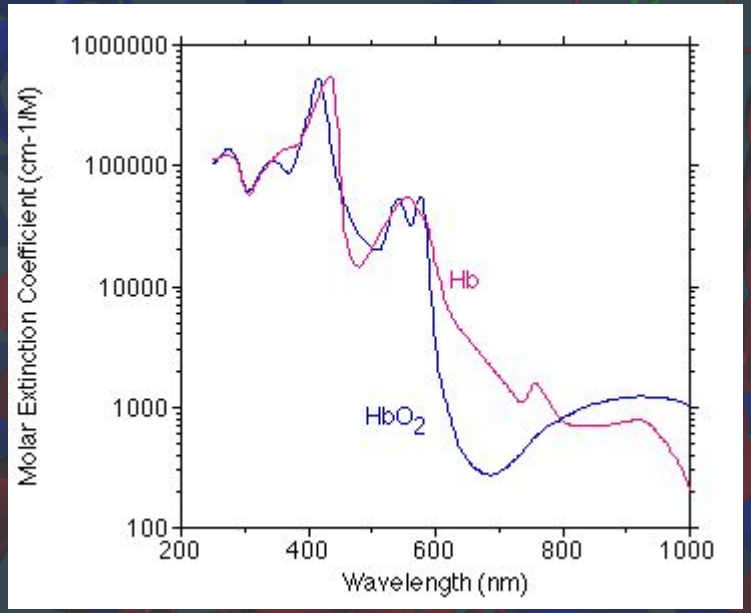
- Hardware
- PCB & Design

Jack Roberts

- Software
- Hardware

Background

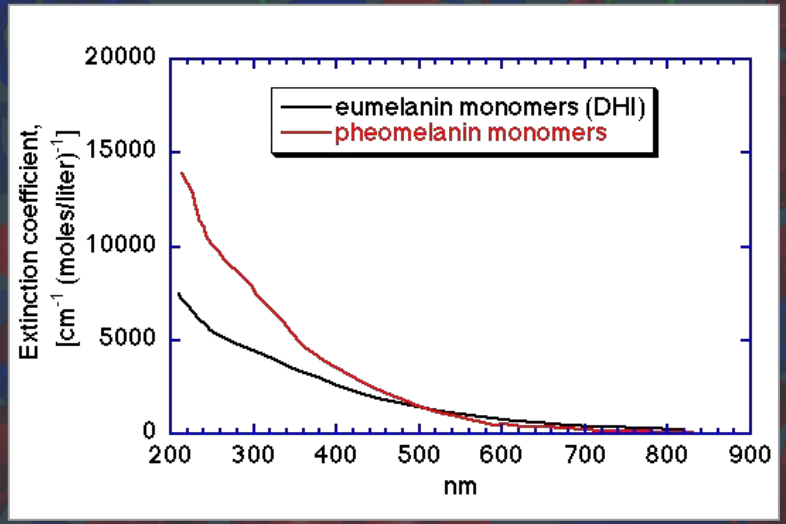
- Oxygen saturation (SpO_2) measured via light absorption of hemoglobin
- Development of noninvasive oximetry
  - From only red (early 1900s) to red-infrared ratio to pulse oximeter ratio-of-ratios (1972)
- (>2) Multiwavelength pulse oximeters uncommon



Graph of the absorption of Hemoglobin by wavelength from “Optical Absorption of Hemoglobin” by Scott Prahl

Background

- Systemic bias in pulse oximetry against dark skin
- Melanin absorbs light leading to an overestimation
- The LOWER the actual blood oxygen saturation is, MORE Overestimation
- Other materials like nail polish and tattoos cause similar issues



Graph of the absorption of Melanin in skin by wavelength from “Extinction Coefficient of Melanin” by Steven Jacques

Beer-Lambert Law

- Relates optical attenuation to the absorption caused by concentrations of substances
- Absorbance due to multiple substances are linear
- To find single concentration in multi-substance materials:
  - Multiple Wavelengths
  - Kramer Method for Systems of Equations
- Coefficients usually empirically found for each pulse ox model

$$-log(T_k) = A_k = \sum_{i=1}^{m} A_{k,i} = d \sum_{i=1}^{m} \epsilon_{k,i} c_i$$

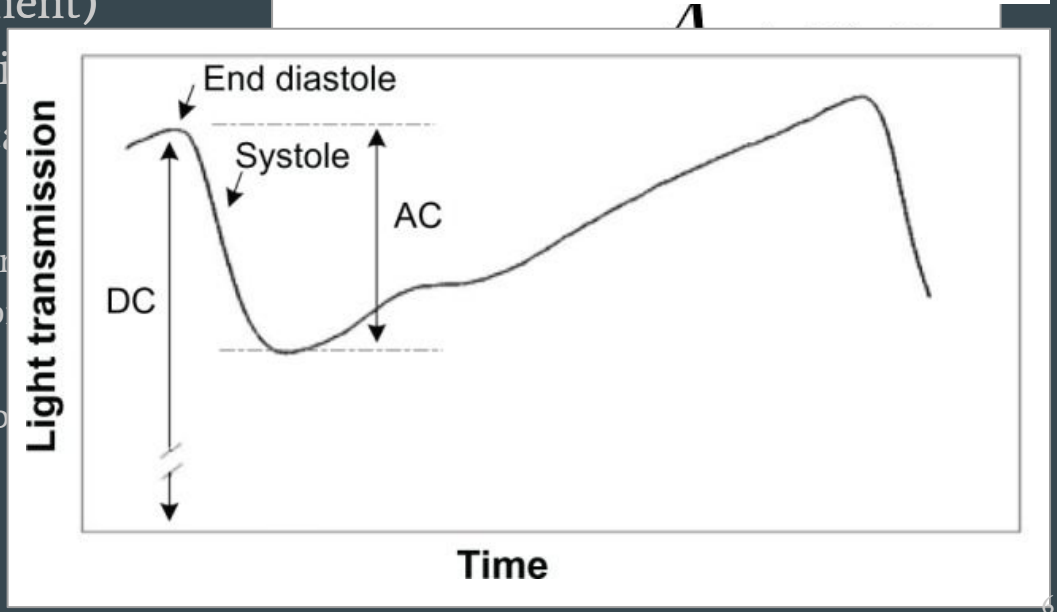
$$S_i = \frac{c_i}{c_o + c_r}$$

For the k-th wavelength:
T_k is Transmission, A_k is Absorbance, d is path length,
c_i is the concentration of the i-th substance,
$\varepsilon_{k,i}$ is the absorptivity or extinction coefficient of the i-th concentration

Pulse Oximetry: Method and Assumptions

- Uses Systole to measure the assumed arterial blood (called the AC component) in comparison to the whole finger (DC component)
- Replace Simple Ratio with a Rati
- Optical gains cancel! Only one c
- Three Assumptions:
  - All Hemoglobin is either HbO2 or r
  - No other absorber is except those p empirical calibration
  - All pulsating volume is arterial bloo

The PPG signal of a pulse oximeter from "Pulse oximetry: fundamentals and technology update"

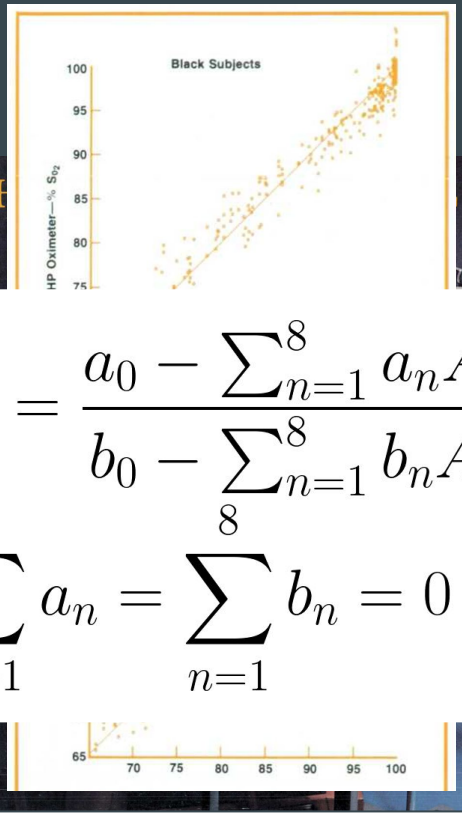


A Path Untread: Gold Standard Forgotten

- ★ Before Pulse Oximetry, HP developed the "Gold Stan
- ★ Ove able pul
- ★ Use
- ★ Tes White subj
- ★ However, no ratios or ratio-of-ratios
- ★ Our project integrate the pulse method with the (>2) multiwavelength method developed by HP

$$S_o = \frac{1 - \sum_{n=1}^{N-1} a_n R_n}{b_0 - \sum_{n=1}^{N-1} b_n R_n}$$

$$R_n = \frac{A_{AC,n}}{A_{DC,n}} \Big/ \frac{A_{AC,NIR}}{A_{DC,NIR}}$$

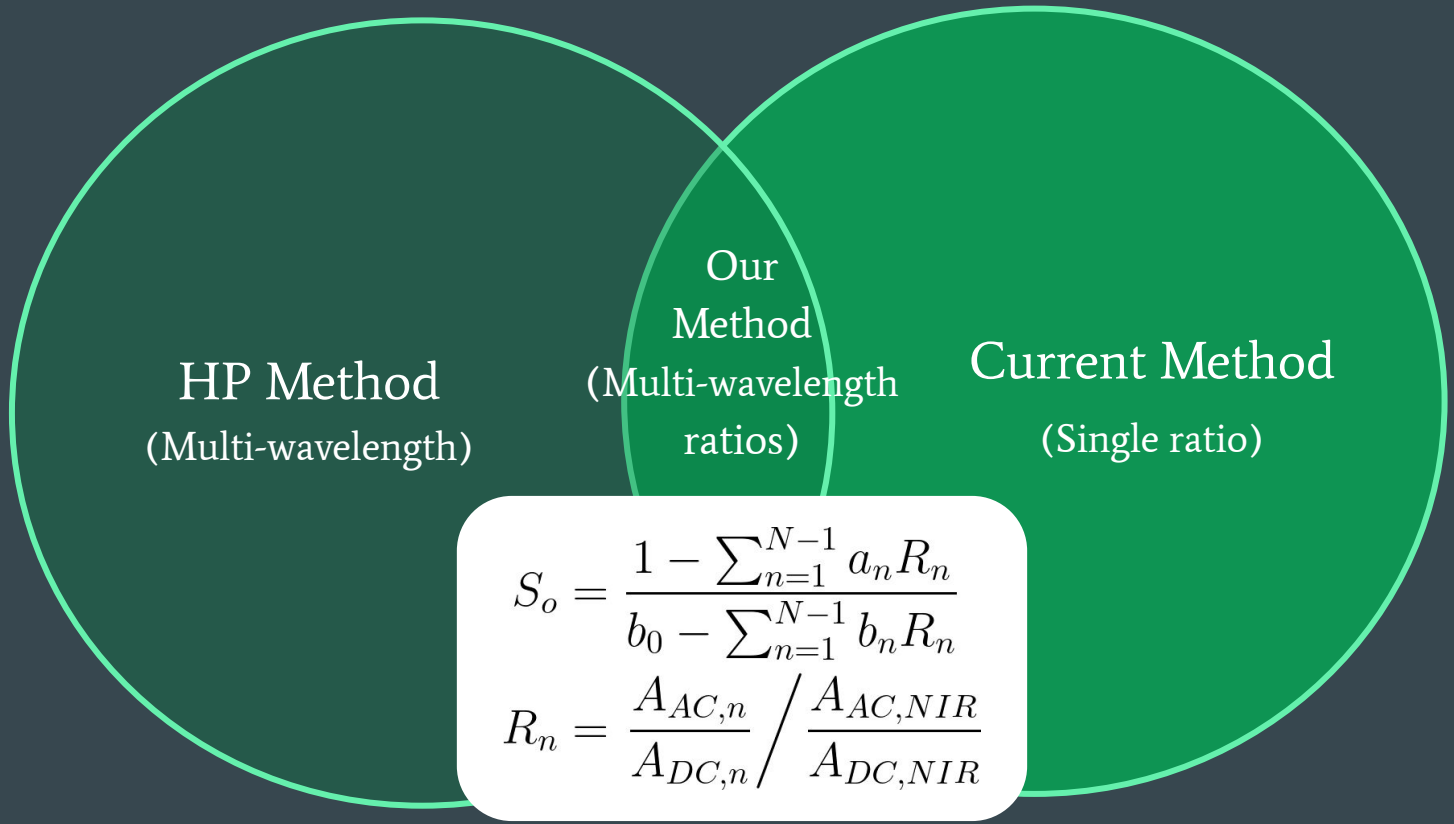


$$S_o = \frac{a_0 - \sum_{n=1}^{8} a_n A_n}{b_0 - \sum_{n=1}^{8} b_n A_n}$$

$$\sum_{n=1}^{8} a_n = \sum_{n=1}^{8} b_n = 0$$

Graphs from "Continuous, Non-Invasive Measurements of Arterial Blood Oxygen Levels" in the October 1976 edition of the HP Journal

Project Overview



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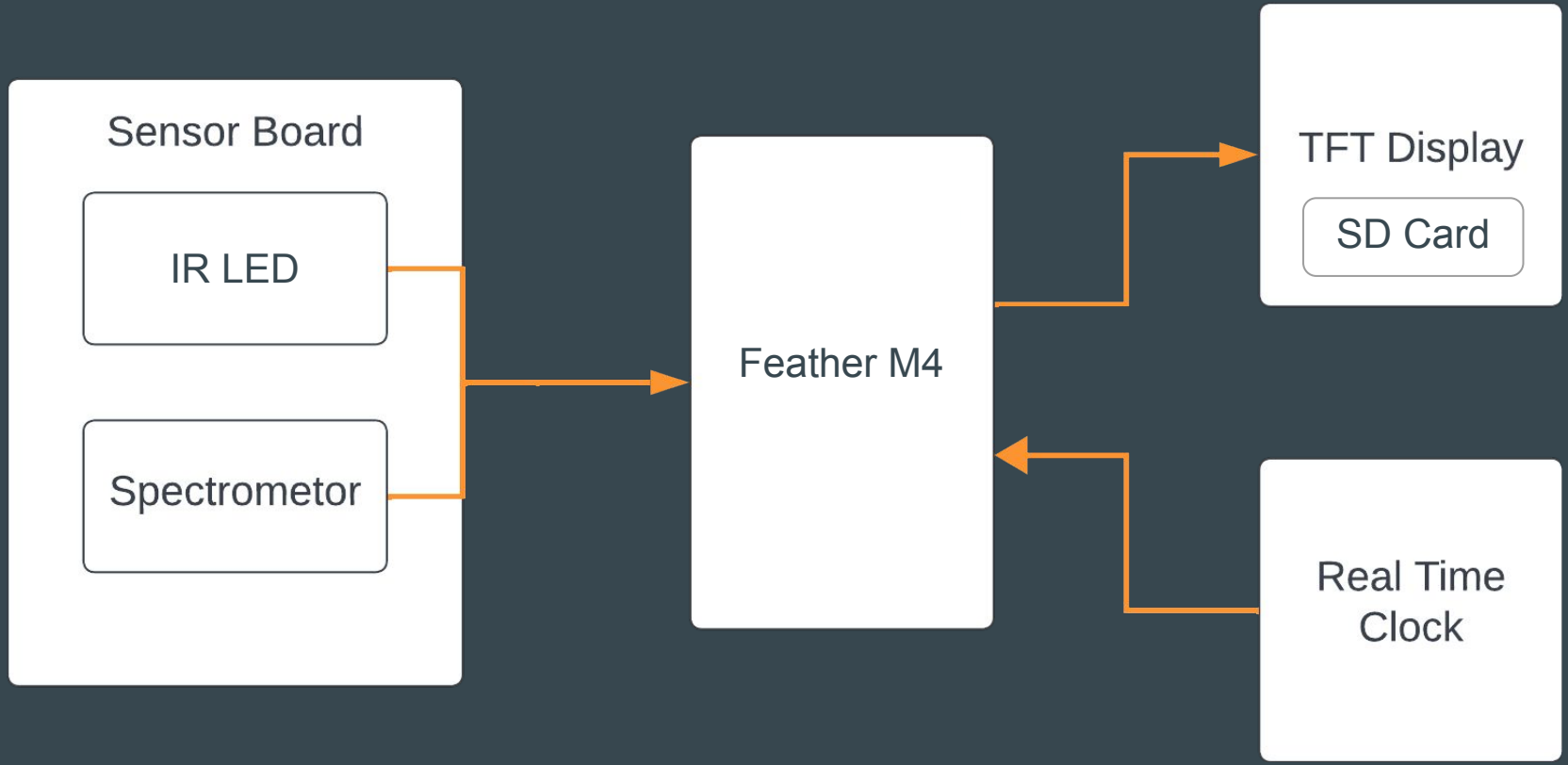
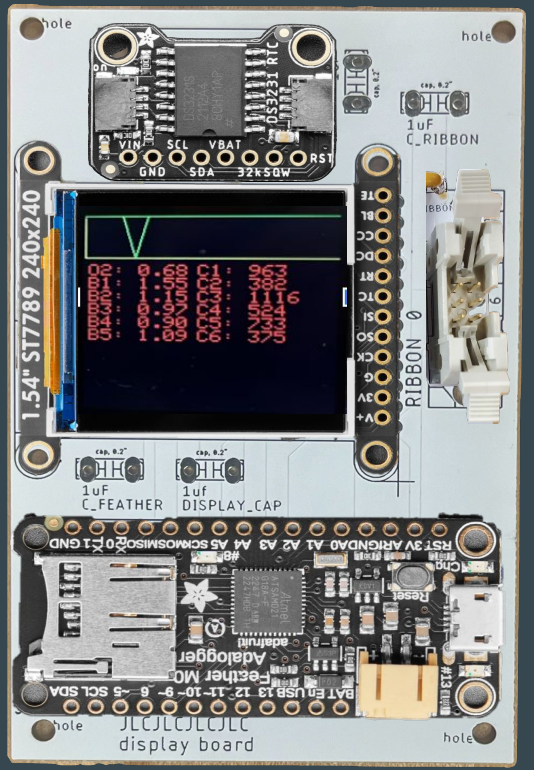
Description of the Device



Main Board



Adafruit DS3231 RTC

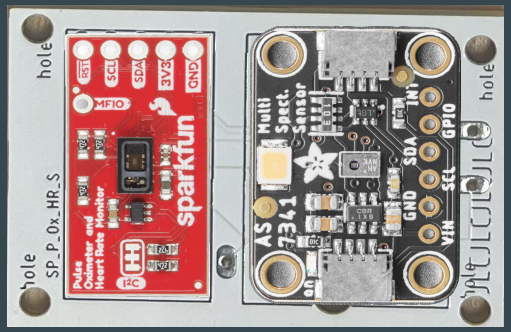
Adafruit Wide Angle TFT LCD Display

Adafruit Feather M4 Adalogger

Ribbon Cable Connector

Sensor Board

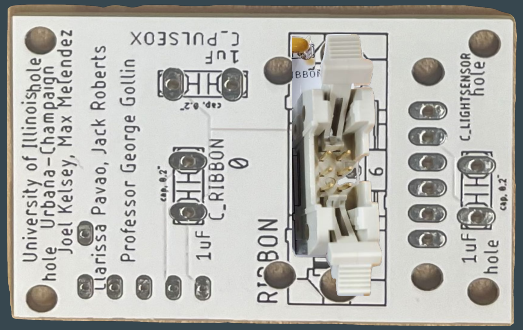
Top



Sparkfun Pulse Oximeter and Heart Rate Monitor

Adafruit AS7341 11 Channel Light/Color Sensor

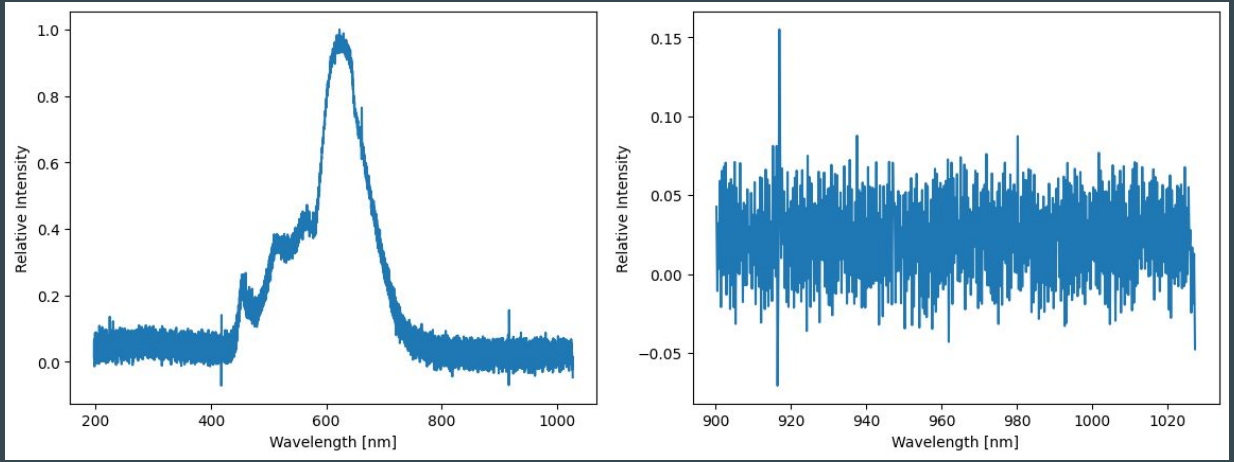
Bottom



Ribbon Cable Connector

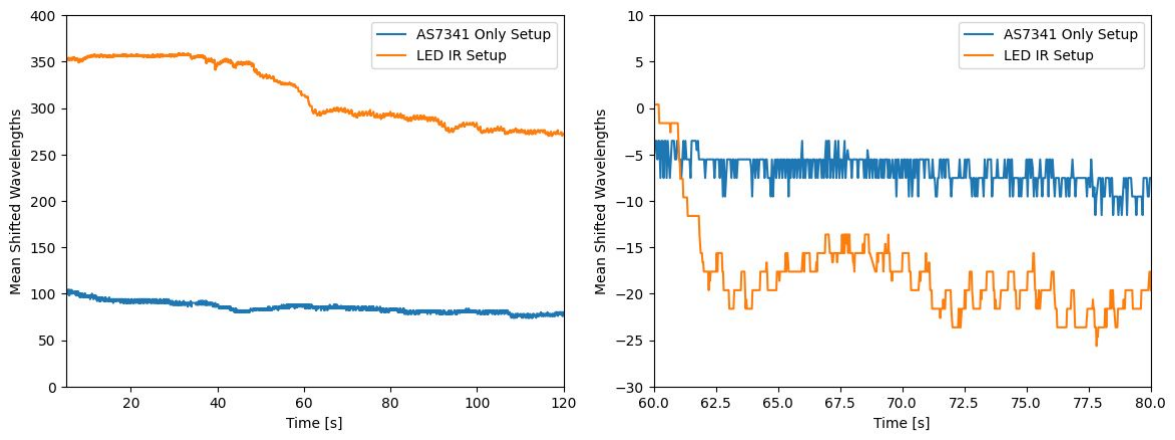
Missing Infrared Component

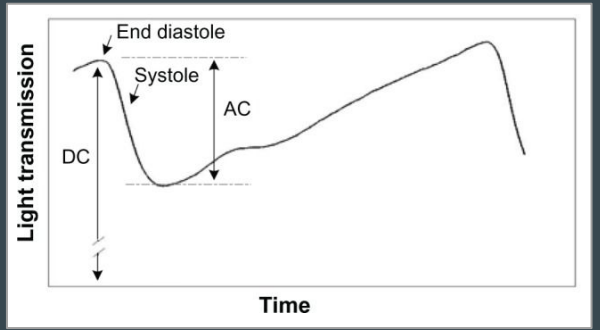
- AS7341 exhibits little-to-no IR component
- Thorlabs CCS200/M - Compact Spectrometer (Extended Range: 200 - 1000 nm)
- Average relative intensity of 0.02264 for 900-1000 nm wavelengths



Missing Infrared Component

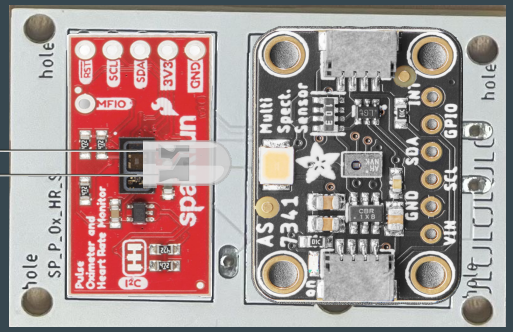
- Replacing the SparkFun pulse oximeter module with an IR LED
- No modulation → clear modulation
- 3x the wavelength counts with IR LED





Sensor Board

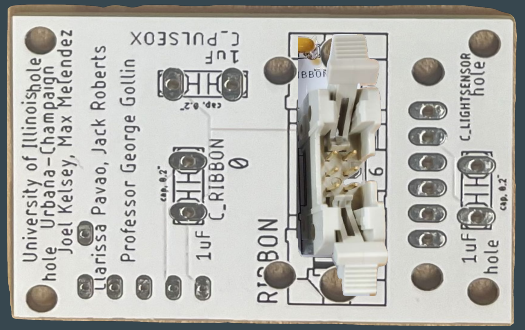
Top



Infrared LED

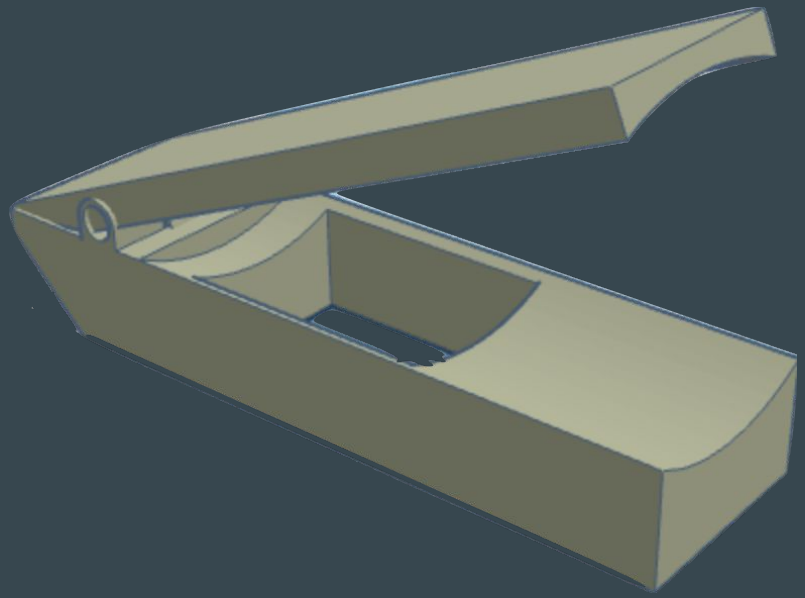
Adafruit AS7341 11 Channel Light/Color Sensor

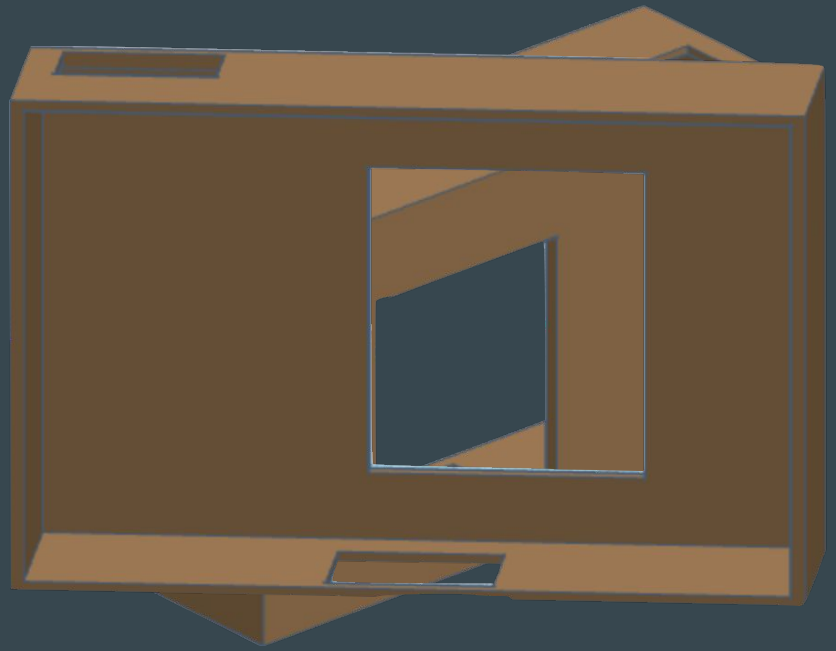
Bottom



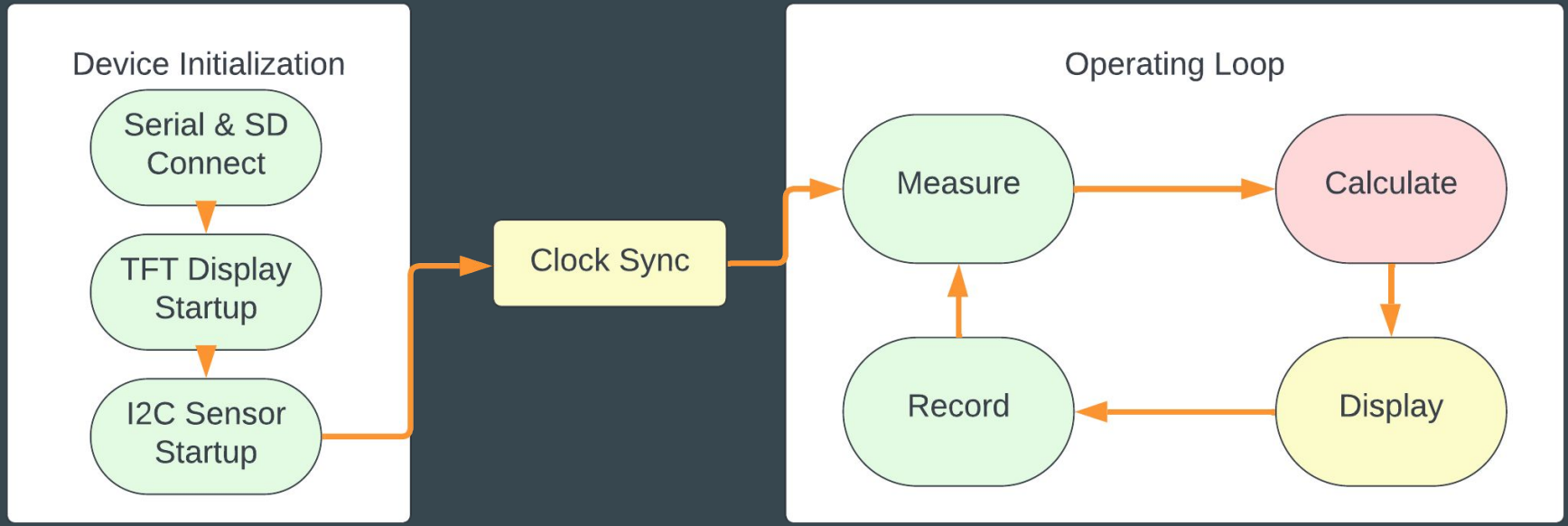
Ribbon Cable Connector

CAD Model

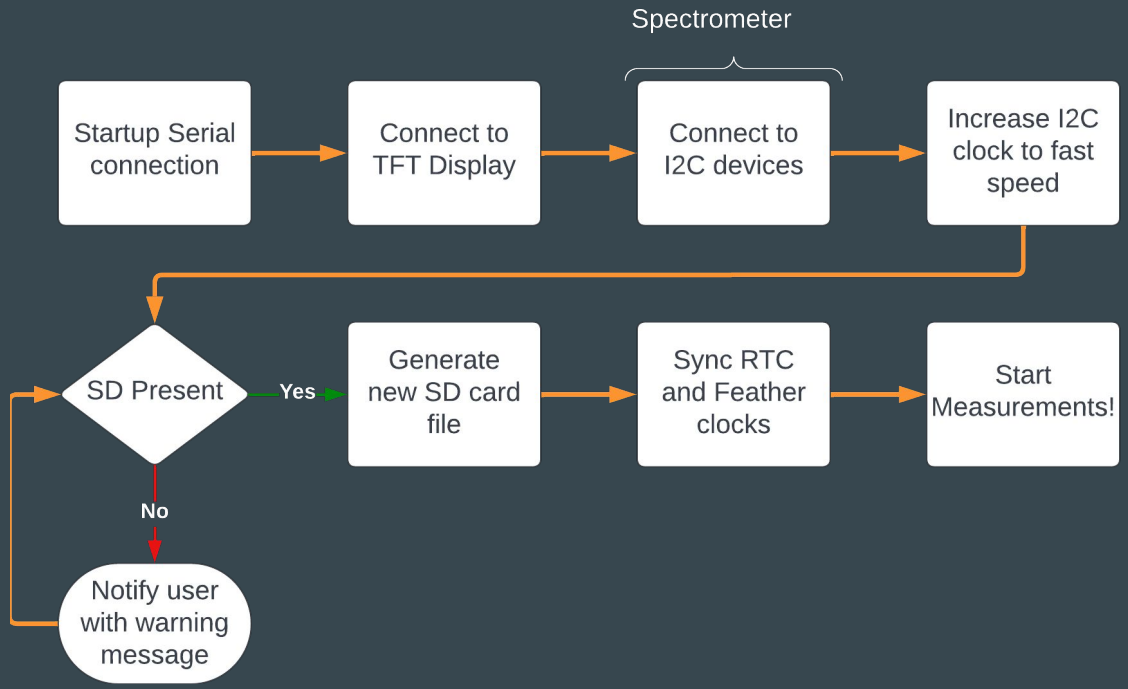




Software

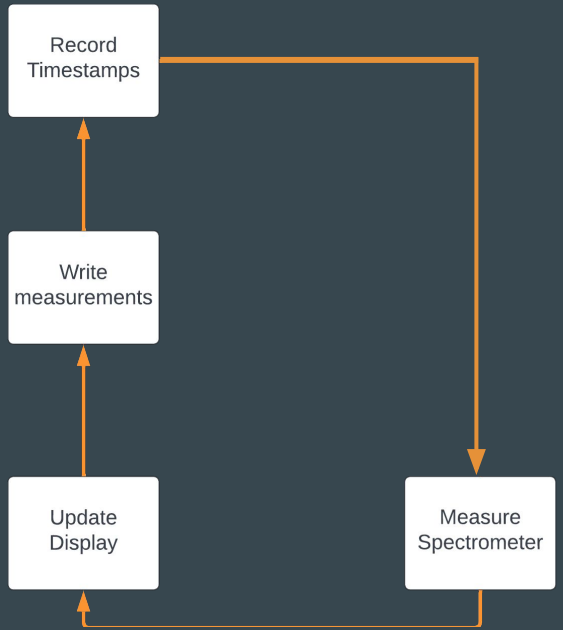

Device Initialization
Serial & SD Connect
TFT Display Startup
I2C Sensor Startup
Clock Sync
Operating Loop
Measure
Calculate
Record
Display

Device Initialization



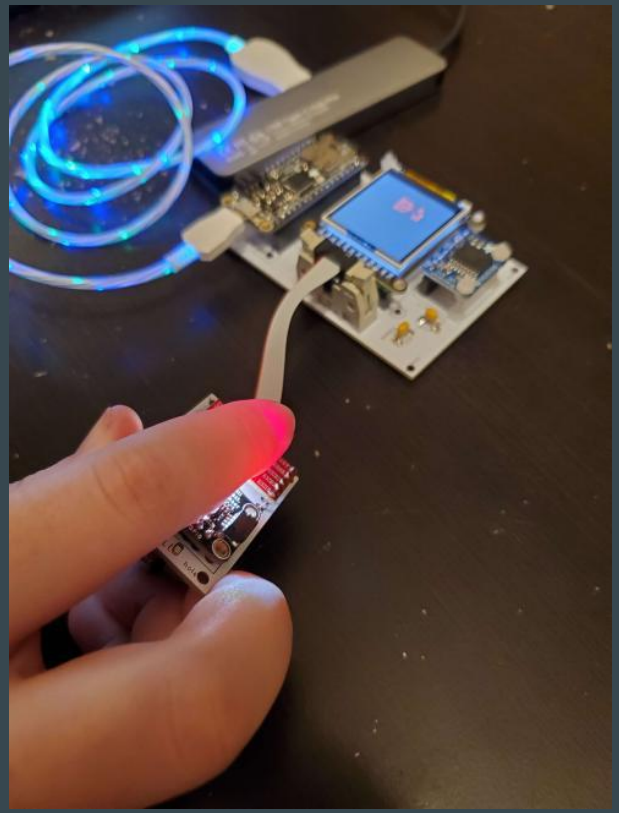
- I2C speed correlates with measurement speed
- Procedure only keeps newest datafile
- Runs when the device is powered on

Operating Loop - Measure



- The loop can only function as fast as the slowest part
- Indefinite Loop: Ends when power is disconnected or SD card is removed

Data Acquisition



- 2 minute measurement
- Timer is started when status 3 is achieved and oxygen saturation can be measured
- Patient remains generally calm
- Right pointer finger is placed with the pulse ox on the far side and the color sensor is closer to user

Data Acquisition

SD CSV Structure

Timing Data

- Real time clock timestamp
  - Unix timestamp
  - Seconds precision
- Feather internal clock timestamp
  - ms precision

Spectrometer Data

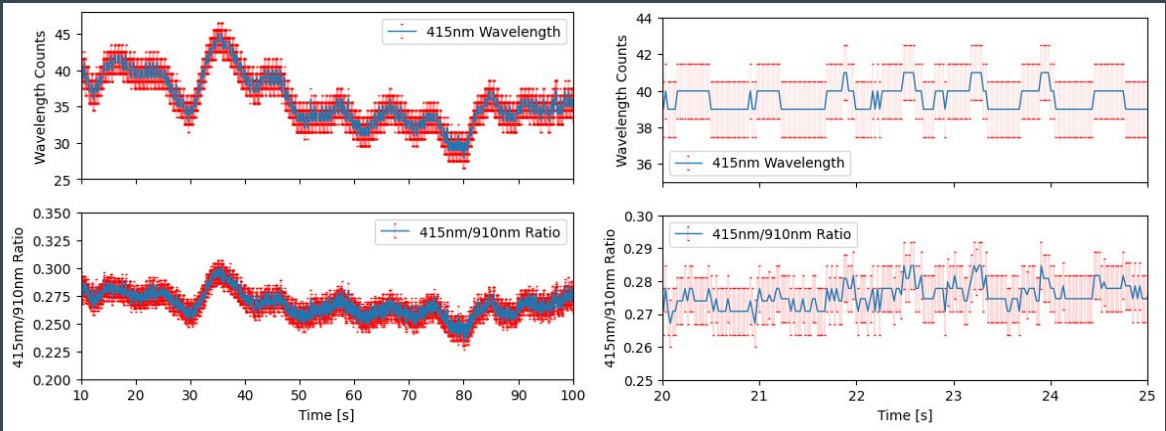
- 11 light channel counts
  - 415 nm - 680 nm
  - 950 nm
  - Clear (unfiltered)
  - Flicker detection

Pulse Oximeter Data

- Beats per minute
- Pulse Ox Confidence
- Oxygen Saturation
- IR & R Counts
- Pulse Ox Status

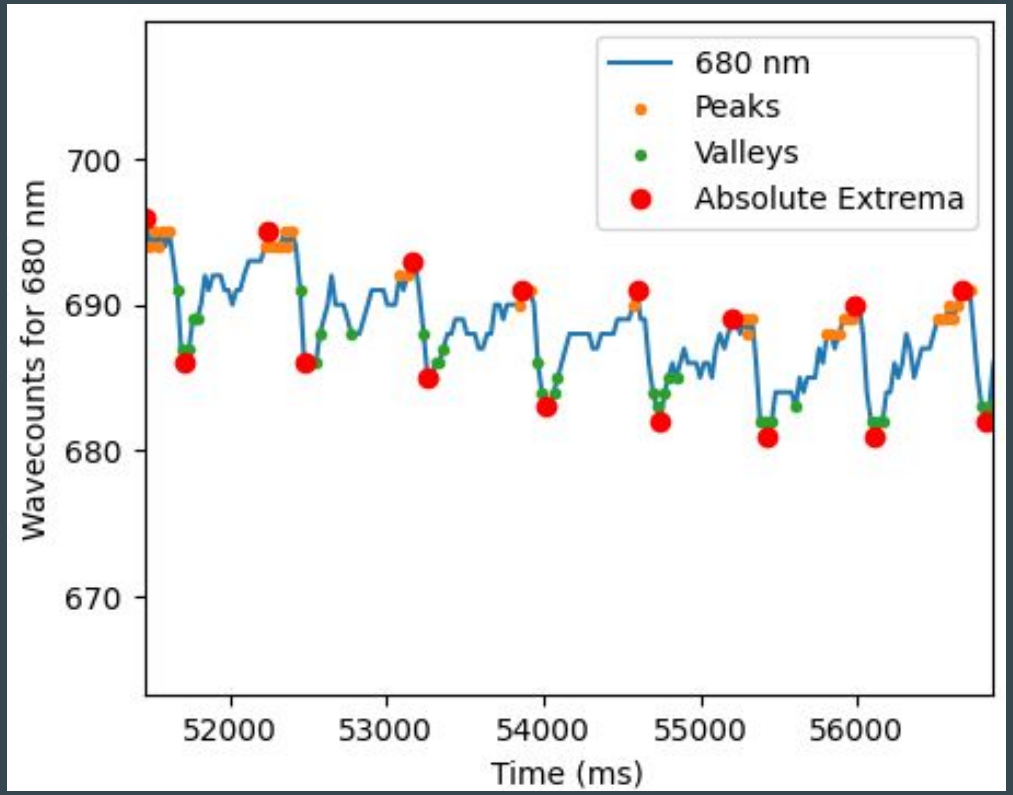
Data & Results

- Raw Data Inputs
- (Top) counts read at the 415 nm wavelength
- (Bottom) Ratio of 415 nm count and 910 nm count
- Raw counts → Ratios → Peak Amplitudes → Algorithm



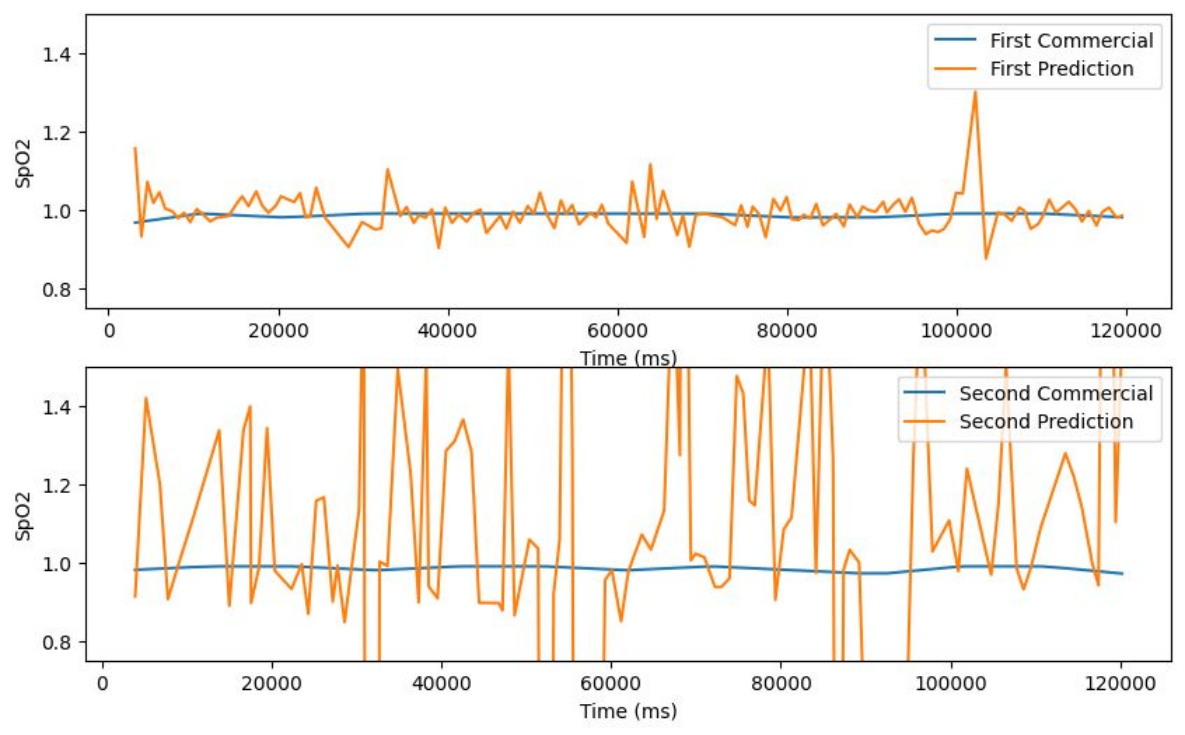
*Error bars at 1 sigma to reflect full-width half-maximum of wavelengths

Data & Results



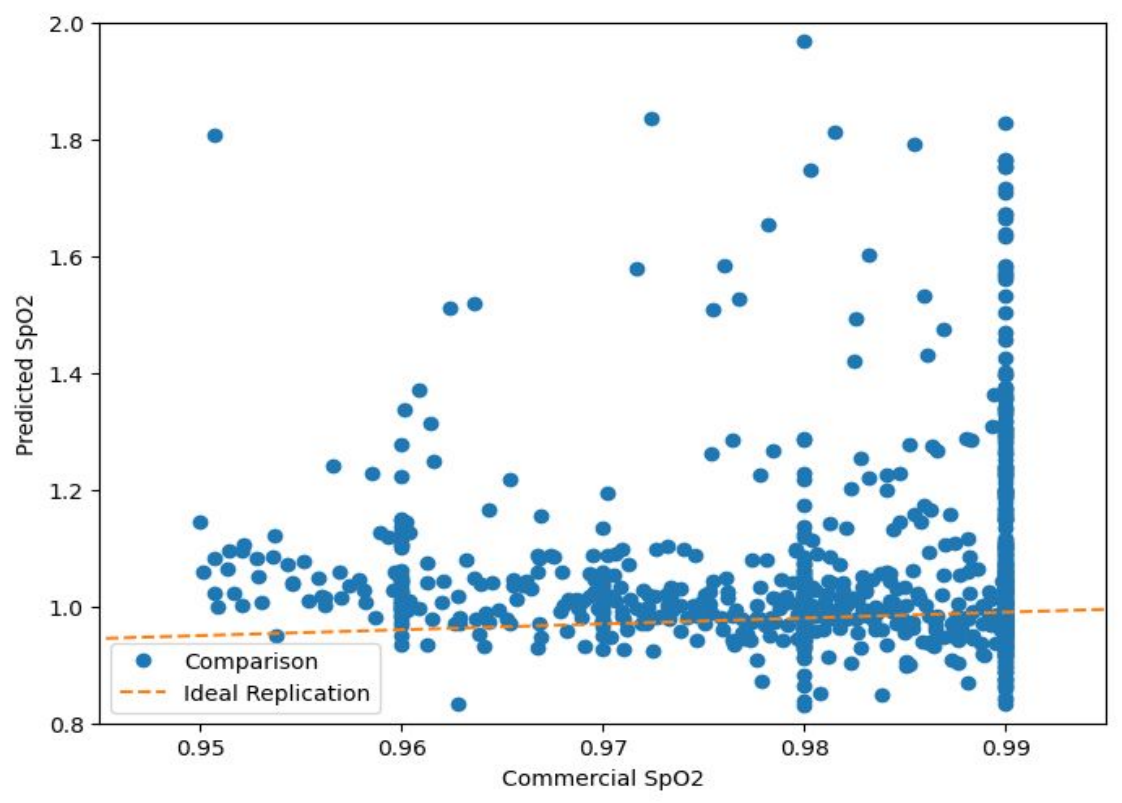
- Peak and valley finding algorithm
- Applied to a raw-data input (680 nm wavelength count)
- For groups of extremes the most extreme value is taken
- Similar results for other channels

Data & Results



- Using previous peaks the ratios of the model can be calculated
- Regression is done using the Gauss-Newton algorithm
- Initial minimization point is having a clear effect

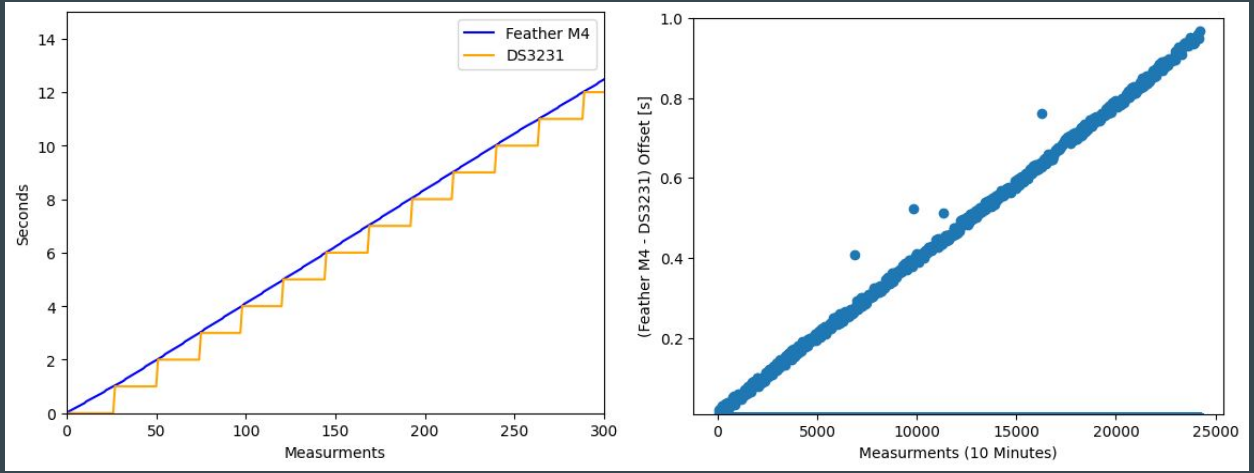
Data & Results



- Ideal would be a linear relationship
- Currently shows high variance
- Potential linear relationship
- Suggests that it could work but needs more analysis

Discussion (Clock Sync)

- Feather M4 timer & DS3231 RTC Sync
- Slight disagreement after a long period of time
- DS3231 lags by 0.194 s in a 110 s measurement/ 0.9679 in a 10 min measurement
- Inconsequential over a short time span



Discussion (Sampling Rate)

- System bottleneck
- Pulse Ox 40-60 mps
- Spectrometer 9-10 mps
- TFT/SD 5 mps
- Measurements can only happen as fast as the slowest module

Discussion (Light Characterization)

Outstanding Problems

- No IR from spectrometer LED

Future Work

- Improve the peak finding code
- Empirical data with the device

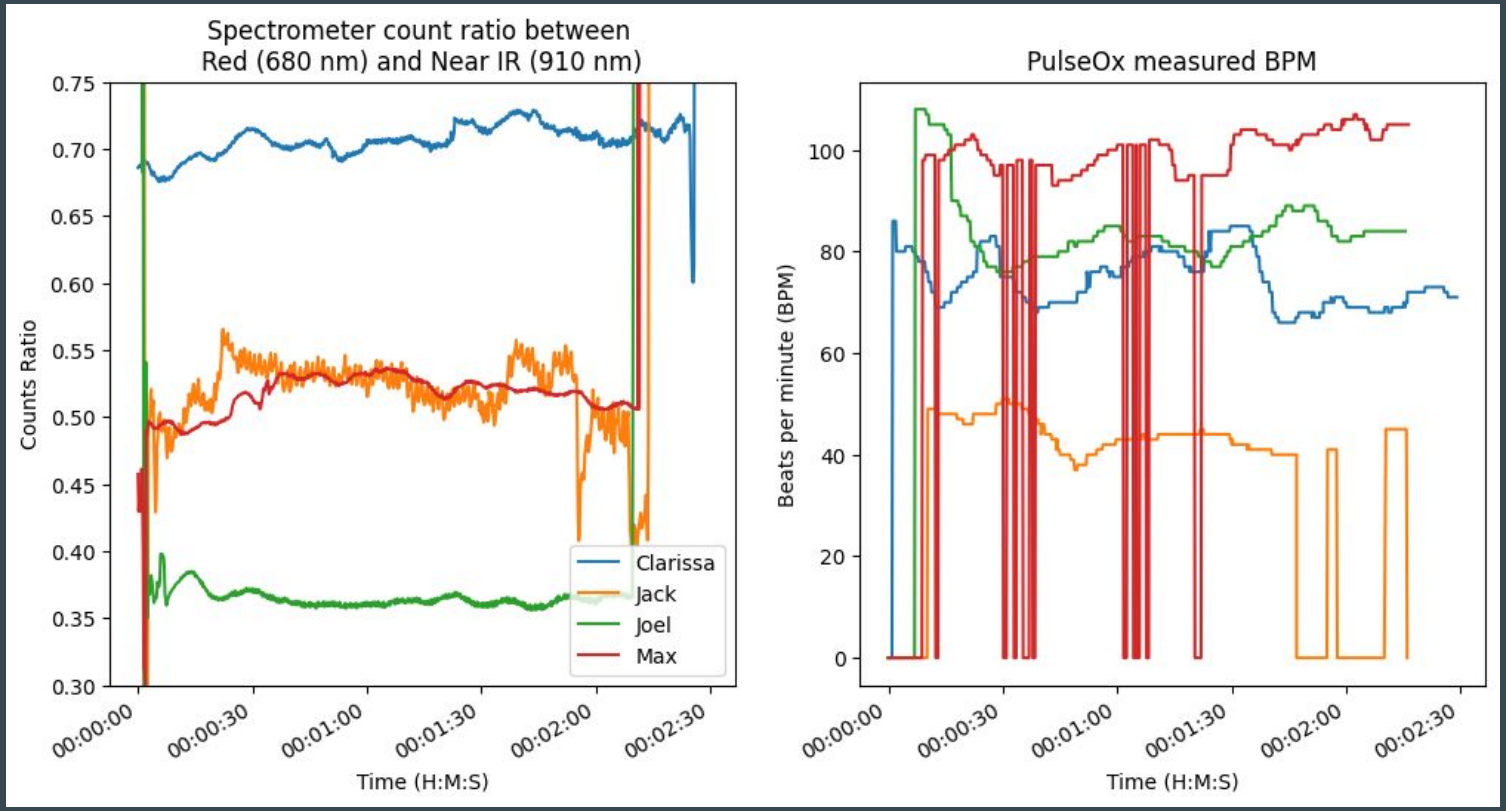
Questions?

Acknowledgements

George Gollin, Yuk Tung Liu and, Shengzhu Yin

Backup Slides

Complete 2 Minute Measurements

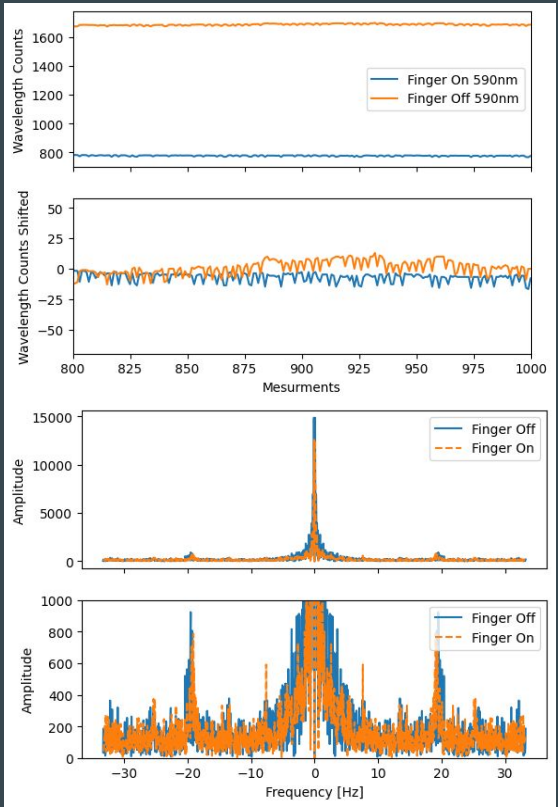


10 channels vs 11 channels

Channel	Center Wavelength [nm] typical	Full Width Half Maximum [nm] typical
F1	415	26
F2	445	30
F3	480	36
F4	515	39
F5	555	39
F6	590	40
F7	630	50
F8	680	52
NIR (Near IR)	910	n/a
Clear	Si response/non filtered	n/a
FD (Flicker Detection)	Si response/non filtered	n/a

- Disagreement between Adafruit and manufacturer
  - Adafruit: 10 channels
  - Manufacturer: 11 channels
- 11 total channels
  - 9 different wavelength bins
    - 415 nm - 910 nm
  - Unfiltered response (Clear)
  - Flicker detection (FD)
    - Detects if the light is flickering
    - Does this count?

Discussion (Finger Displacement)



- Finger pressed on sensor vs finger hovering 2 mm above
- Higher amplitudes from finger off
- Peak at 20 Hz, Sampling rate ~22.5 Hz average
- Too much noise when finger is off, introduces error source