Multi-Sensor Suite for Melanin-Adjusted Blood Oxygenation Measurement Progress Report

Ricky Kanak and Leron Maddi
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois, 61801
December 2, 2024

Abstract

This project aims to develop a cost-effective medical device that performs skin color-corrected measurements of a patient's heartbeat, blood oxygenation, and blood pressure to create a more consistent healthcare device. The apparatus comprises two AS7341 10-channel Light Sensors, two analog single-channel light sensors, and Arduino-based analysis software integrated through an Adafruit Feather M4 Express and custom PCB. The successful integration of hardware and data collection techniques has propelled this project into the data analysis and PCB design phase. Current challenges include replicable calibration techniques and sampling frequency optimization.

1 Introduction

Patients rely on personal medical devices to provide accurate and reliable information, empowering them to be proactive in preventative healthcare. Unfortunately, current portable pulse oximeters fail to address the effect of melanin on signal transmission through a patient "resulting in overestimations with increased incidence in the risk for occult hypoxemia despite normal SpO2." (Cabanas, Ana M et al.). A distinction in the quality of care based on a patient's skin color highlights the need for inclusive medical devices to eliminate disparities in diagnostics and preventative medicine.

This project aims to address this inequity by addressing the shortcomings of current commercial pulse oximeters through skin color correction. Our solution is a cost-effective device that monitors heartbeat, pulse oxygenation, and blood pressure adjusted for patient melanin levels. This device will provide more accurate and equitable diagnostics by leveraging the AS7341 10-Channel Light Sensor, custom analog pulse sensors, and Arduino-based analysis software. Successful implementation of this device has the potential to improve the quality of life for people who proactively monitor their health.

This report will explore the current progress in creating this device, the underlying physical principles, the theory behind the signal analysis, and different strategies for optimizing each process.

2 Theory

This device relies on the interaction of light with human tissue, exploiting the principles of light transmission, reflection, and absorption. The Arduino AS7341 10-channel spectral sensor

measures light intensity across multiple wavelengths. Each channel corresponds to a specific wavelength range, enabling precise hematological analysis.

Measurements begin when light is emitted into the skin and interacts with various tissues, including blood vessels. Blood vessels are part of the circulatory system and help transport blood throughout the human body. As the heart pumps blood through blood vessels, they absorb and reflect light differently based on their size, determined by the volume of blood passing through. These physical attributes dynamically change as the heart passes through the diastolic and systolic phases, creating pressure waves that modulate the light intensities detected by the sensors. Observing these signals produces a Photoplethysmography (PPG) signal, the backbone of our measurements.

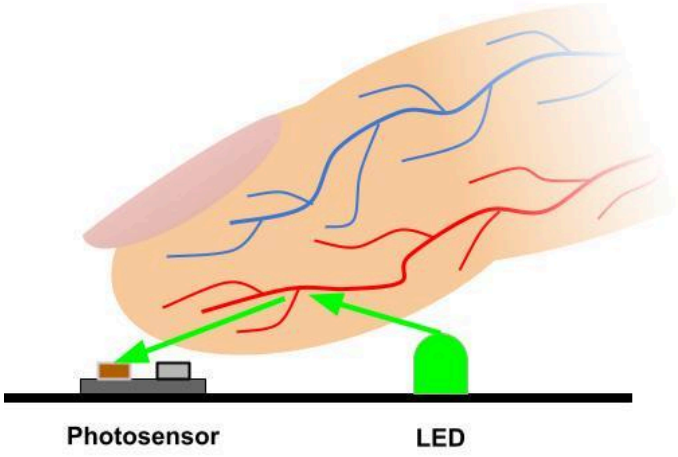

Figure 1. Diagram illustrating the principles of PPG. The green LED emits light into the finger tissue, where photons are scattered by the surrounding biological structures. A photo sensor detects the scattered photons emitted from the skin. Changes in arterial blood flow modulate the scattering dynamics of photons, enabling the detection of a PPG signal.

This device will expand on current pulse oximetry technology by incorporating skin color calibration and measuring additional cardiovascular metrics. While traditional pulse oximeters compare the intensities of transmitted red and near infrared (NIR) light to estimate blood oxygen saturation, this system will use additional green wavelengths to extract data from a broader spectrum. The AS7341 sensors will be used to measure variations in the transmission of scattered light, accounting for differences in skin tone, to improve accurate performance across diverse populations.

In addition to pulse oxygenation measurements, measuring PPG signals at two locations along the circulatory system provides enough data to calculate pulse transit time (PTT) by cross-correlation. “Pulse transit time (PTT)… …has been developed as a novel cuffless form of continuous [diastolic] blood pressure monitoring.” (Hoshide et al.) If successful, this approach could expand the capabilities of pulse oximetry and non-invasive patient monitoring devices.

2.1 Theory: Blood Oxygenation from Ratio of Red to NIR absorption

Blood oxygenation measurement is achieved through taking the ratio of absorption/transmission readings for red light (680 nm) and near infrared light (910 - 940 nm) and using reference charts to determine the corresponding SpO2 value. These reference charts (Azhar et al.) are determined empirically.

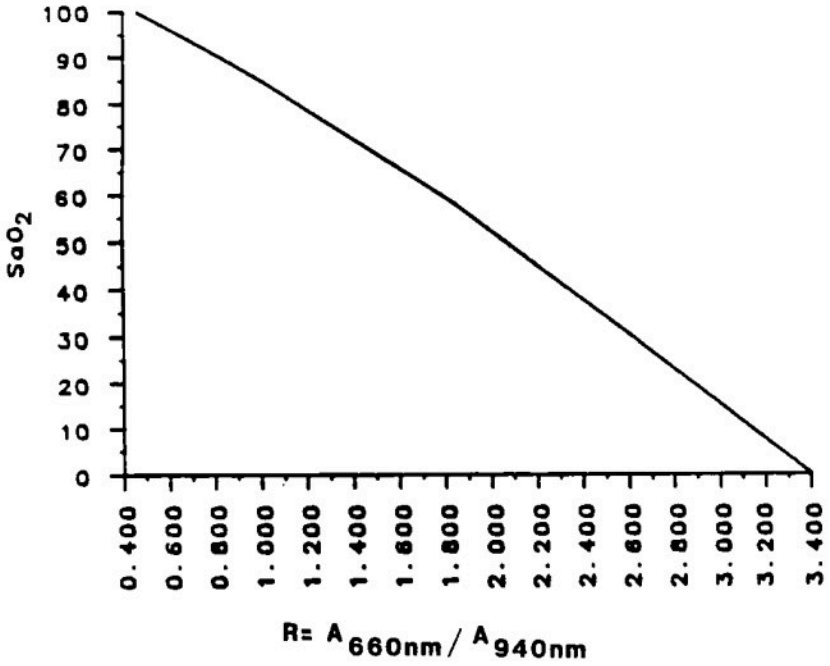

Figure 2. Reference chart for SpO2 determination (Yartsev). Empirically derived SpO_2 values plotted against the ratio of transmission signals of Red light (660 nm) to Near Infrared light (940 nm).

The significance of the signal ratio between these two wavelengths is due to hemoglobin having different absorption/transmission characteristics based on its oxygenation state. Oxygenated hemoglobin (HbO_2) absorbs more infrared light and less red light, while deoxygenated hemoglobin (Hb) absorbs more red light and less infrared light (Figure 3). By comparing the relative absorption of these wavelengths, a pulse oximeter can determine the proportion of oxygenated hemoglobin in the blood.

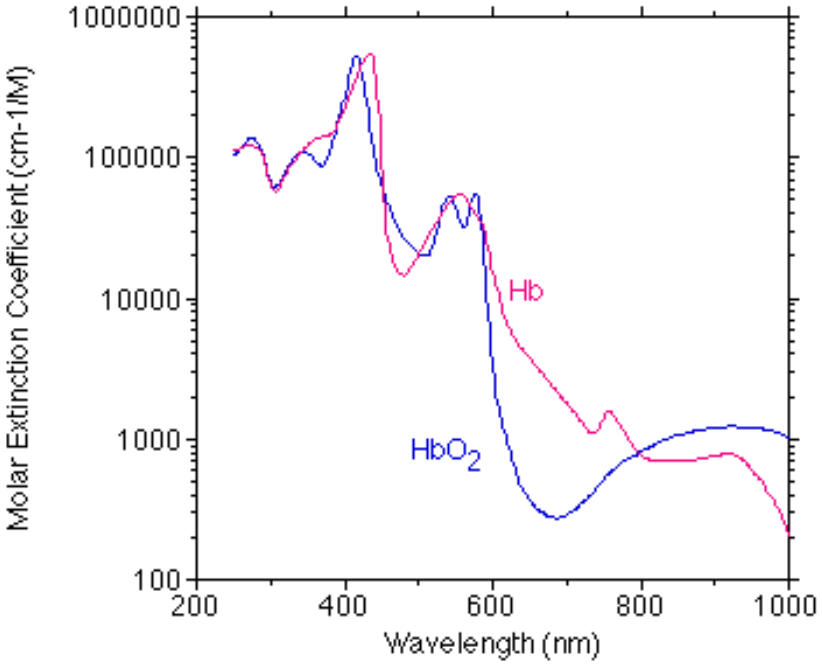

Figure 3. Hemoglobin Absorption Characteristics by Wavelength (Prahl). Hb absorbs significantly more 680 nm light than HbO_2 but Hb and HbO_2 absorb approximately the same amount of light at wavelengths in the near infrared (800 nm-1000 nm). The ratio of 680 nm light absorption to NIR light absorption for a sample indicates the oxygenation of hemoglobin as a higher ratio will result from higher concentration of Hb relative to HbO_2.

The meter uses photoplethysmography (PPG) to detect the pulsatile component of blood flow representing arterial blood, as blood volume changes with each heartbeat absorption of light fluctuates. The ratio of these fluctuations at red and NIR wavelengths can be used to determine the SpO2 value. The ratio (R) value can alternatively be represented as the ratio of AC and DC signals instead of the ratio of Red/NIR light, with the benefit of reducing the effects of artifacts, skin color, tissue thickness, and ambient light. This alternate "ratio of ratios" measurement is determined as follows (Chan et al.):

(1) $$R = \frac{AC_{Red}/DC_{Red}}{AC_{NIR}/DC_{NIR}}$$

Here alternating current (AC) represents the pulsatile (arterial) component of the signal, and the direct current (DC) represents the non-pulsatile (venous, tissue, constant light absorption) component of the signal. For further details, see Appendix A.

SpO2 refers to what percentage of the blood is saturated with oxygen and is determined as follows (Oertel and Burghardt):

(2) $$SpO_{2\_} = \frac{HbO_2}{HbO_2 + Hb}$$

Beyond determination of blood oxygenation, it may be possible to take the phase difference between readings from sensors at different points on the arm to determine bulk blood velocity. Simply, the velocity between readings at two points would be determined by taking the phase difference ($\boldsymbol{\Delta\Phi}$) in radians between the two signals and using it to determine the time delay as follows:

(3) $$\boldsymbol{\Delta} t = \frac{\boldsymbol{\Delta\Phi}}{2\boldsymbol{\pi} f}$$

Here frequency (ƒ) would be determined by using fourier analysis to determine the dominant frequency present in the pulse signal. Then the pulse wave velocity (PWV) would be determined using distance between the sensors and the time delay above:

(4) $$PWV = \frac{d}{\boldsymbol{\Delta} t}$$

3 Hardware

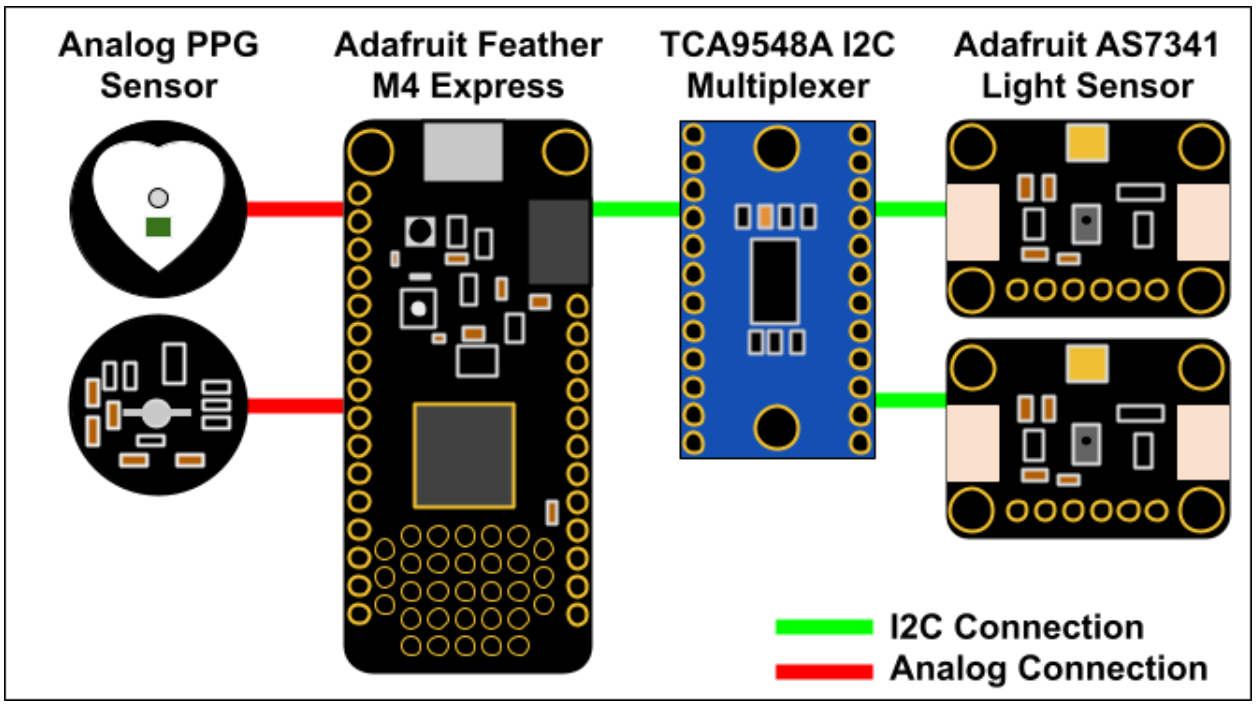

Figure 4. Diagram of the current hardware configuration. Two analog PPG sensors are connected to the Adafruit Feather M4 Express through analog inputs, while the TCA9548A I2C Multiplexer interfaces two Adafruit AS7341 10-Channel light sensors with the microcontroller through I2C communication.

3.1 Hardware: Components

The device consists of five key hardware components: two single-channel analog light sensors, two AS7341 10-channel light sensors, a TCA9548A I2C multiplexer, an Adafruit Feather M4 Express microcontroller, and a custom-designed PCB to integrate and house all components.

The two single-channel analog light sensors emit a constant green light at 565 nm into the patient's skin. Reflected light intensity is recorded by onboard photodiodes. Analog sensors offer a significant advantage over digital sensors by eliminating any onboard conversion of analog signals to digital. This design allows these two sensors to sample at 2 kHz, sufficient to capture detailed photoplethysmography (PPG) signals. Cross-correlation techniques are used to determine the pulse transit time (PTT) across the 5 cm of blood vessels with a resolution of 0.5 ms. “Pulse transit time (PTT) provides a basis for ubiquitous blood pressure (BP) monitoring.” (Mukkamala, Ramakrishna et al)

The AS7341 10-channel light sensors enhance the single-channel sensors by analyzing reflected light across ten distinct wavelengths, providing significantly more detailed spectral data. The AS7341 achieves this spectral range with a 4x4 photodiode array and six integrated analog-to-digital converters (ADCs). While the onboard ADC enables wider spectral resolution,

the integration time required to integrate each signal from the photodiode grid limits the sensor's sampling frequency to 10 Hz. This lower sampling rate, compared to the single-channel analog sensors, enables the AS7341 to monitor a patient's pulse and assess their skin color.

This device is powered by the ATSAMD51 32-bit Cortex M4 processor on the Adafruit Feather M4 Express, with a clock speed of 120 MHz. The microcontroller records data from all four sensors and executes programmed data analysis algorithms. However, the Feather's single I2C channel poses a bottleneck when interfacing with multiple I2C devices. To address this, the TCA9548A I2C multiplexer manages communications between I2C sensors and the microcontroller.

All components are currently oriented on a breadboard (Figure 5) to minimize the overall footprint while positioning each sensor for optimal recording. A PCB will be developed in EAGLE and optimized for performance.

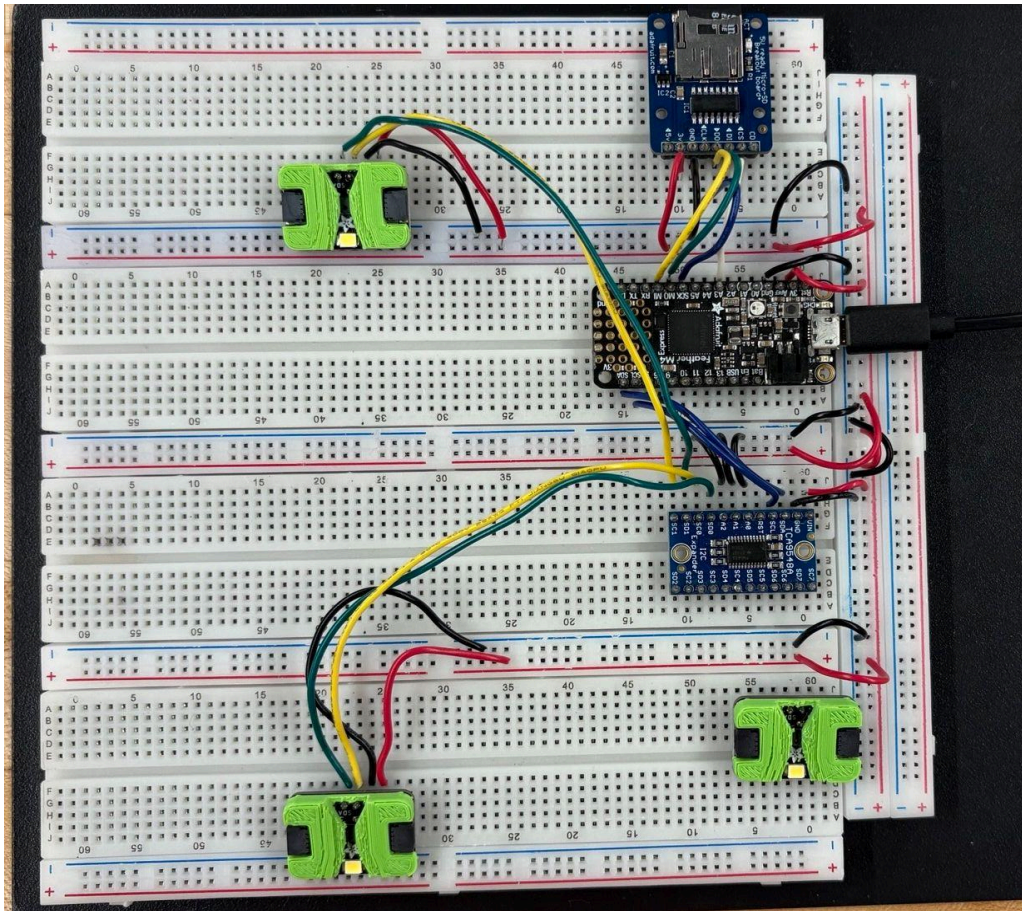

Figure 5. Example of AS7341 breadboard setup to measure transmission signals. AS7341 sensors (green) are capped with 3D printed ramps to allow for effective light transmission through skin. The two sensors are run through a TCA9548A multiplexer utilizing I2C. The system is integrated through an Adafruit Feather M4 microprocessor.

3.2 Hardware: Calibration and Limitations

Together, the four sensors provide a balance of precision and versatility. The high-speed sampling capabilities of the single-channel analog sensors ensure accurate pulse transit time measurements, while the AS7341 sensors contribute valuable spectral data for heartbeat monitoring and skin tone correction. The analog sensor offers excellent temporal resolution, vital for calculating a precise pulse transit time, whereas the AS7341 sensors complement these measurements by analyzing multiple wavelengths.

The stability and reliability of these sensors depend on their proximity to the patient's skin and any motion artifacts. To mitigate these issues, a casing will be designed to securely attach the device to the patient, reducing signal degradation and minimizing linear trends. However, one limitation of both sensor types is their sampling rate. When the sampling demands of these sensors exceed their capabilities, the resulting readings are inconsistent and inaccurate, failing to respond to dynamic inputs. Without formal error messages, the sampling limits were determined through trial and error while comparing the sensor results with a commercial pulse oximeter.

4 Software

Sensor measurements were taken using Arduino based C++, allowing for manipulation of parameters such as the rate at which sensors collect data and in the case of the AS7341, which channels are being actively read. Data from sensors are saved to SD cards as text files on Arduino IDE, which are then analyzed using Python. Graphing and data analysis are achieved through use of Python scripts run through Spyder. For the pulse measurement sensor, these scripts produce cross correlation graphs. For the AS7341 sensor, scripts produce graphs displaying pulse measurements with smoothing, histograms to display time differences between readings, and fourier analyses to determine the beats per minute (BPM) (see Appendix G).

Arduino IDE code for the AS7341 sensor sets up and defines the sensors and which channels will be used. The AS7341 has two banks which each contain half of the available wavelength channels and a NIR and CLEAR channel each. The banks are labelled “high” and “low”, with the high bank containing longer wavelengths and the low bank containing shorter wavelengths. A multiplexer on the sensor reads both banks when using the *readAllChannels* function. For our purposes we are interested in longer wavelengths, particularly NIR (800 nm to 1000 nm) and wavelengths of red light (680 nm and 630 nm), which naturally leads us to selecting the high bank alone to improve data acquisition speed. This process involves adding additional functions to the script to achieve similar functionality as *readAllChannels*, and then choosing specific color channels by selecting their corresponding ADC channels from the high bank. The data are then saved into an array and written into the text file. When reading multiple AS7341 sensors, the data is written with alternating readings reading sensor 1, sensor 2, sensor 1, etc.. This allows for us to separate the data in Python by alternating rows for analysis.

The single-channel analog pulse sensors transmit data from the photodiode to an analog input on the Feather M4 Express. The microcontrollers onboard ADC convert the sensor signal

intensity into discrete voltage values. These intensity values and their corresponding measurement times are saved to an SD card for analysis. The analysis process begins by smoothing raw PPG signals using the NeuroKit2 Python package, designed to process and analyze biological signals for research purposes. Once the PPG waveform is cleaned, a Fast Fourier Transform is applied to isolate the fundamental frequency corresponding to the patient's heartbeat. After calculating the pulse frequency in beats per minute, the two PPG signals are cross-correlated over the first two seconds to determine the pulse transit time.

4.1 Calibration

Initial experimentation utilized an AS7341 10-channel sensor script which read from all 10 of the sensor's channels at once, with the function *readAllChannels,* to obtain transmission measurements. In order to improve data acquisition speed, reading individual channels was attempted. This process involved utilizing a different function, *readChannel*, which could read individual ADC channels from both banks on the device. The identities of the channels referred to by different ADC channels were found in datasheets and verified through experimentation with single color LEDs. An issue which arose from this process was encountering duplicate measurements caused by the script recording the data contained on the sensor's bank multiple times before the bank refreshed. The solution to this problem was found in utilizing the function *delayForData* to assure that data was only recorded once the bank had refreshed. It is worth noting that decent data was produced with the samples with duplicates as a smoothing function was employed. The function applied a rolling average to the data with a window length corresponding to approximately one heart beat. This effectively smoothed over the "plateaus" which would occur in the graphs due to duplicates.

4.2 Precision and Stability

Early tests of the validity of the BPM measurements were found to be accurate to <2 beats per minute relative to a commercial pulse oximeter. The AS7341 sensor was found to have a delay of ~100 milliseconds between readings (Figure 6) with *readAllChannels*, and ~15 milliseconds between measurements while reading individual channels with *readChannel* and *delayForData.*

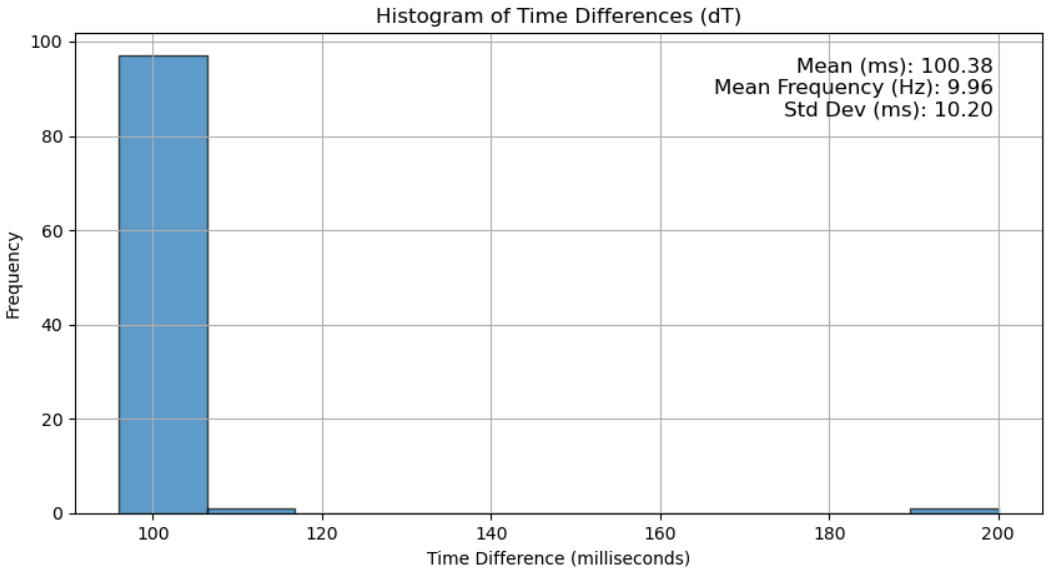

Figure 6. Histogram showing the distribution of time differences between subsequent transmission intensity measurements recorded using the readAllChannels setting on the AS7341 sensors. The mean time difference is 100.38 ms, with a standard deviation of 10.20 ms. The corresponding mean frequency of measurements is 9.96 Hz. For additional histograms, see Appendix B.

5 Data & Results

Data acquisition involves collecting light transmission signals through the Adafruit AS7341 10-channel sensor and the single-channel analog pulse sensor to produce a graph depicting a pulse waveform. From this signal and its properties various information is obtained and derived, including heart rate, blood oxygenation, and pulse transit times. The goal of this project is to better utilize and interpret the core absorbance/transmission signal that pulse oximeters and similar medical devices rely on, with the aim of developing more effective and comprehensive measurement devices.

5.1 Limitations

Currently we have not employed a method to ensure consistent finger pressure and coverage over the AS7341 sensor beyond 3D printed ramp/spacer covers. This leads to some inconsistencies and irregularities in the data caused by small movements of the hand and increasing or relaxing pressure on the sensor. Future design iterations will also aim to allow for multiple sensors to be placed at various points on the hand to collect multipoint measurements; this will require a redesign of the sensor covers to allow for better coverage on non finger tip areas as well as a means for consistent and measurable spacing between the sensors.

5.2 Analysis

The analysis phase of this project focuses on processing raw data collected by the four onboard sensors to extract meaningful metrics. Data from the AS7341 sensors are used to calculate wavelength-specific absorption ratios that indicate the oxygenation of the patient's blood while correcting for melanin concentration. Fourier analyses are applied to isolate dominant frequencies in the PPG signals to provide precise measurements of the patient's pulse (Figure 7). For the analog sensors, cross-correlation is used to determine the time delay of the PPG signals across sensors to determine the pulse wave velocity (PWV) and blood pressure.

The primary processing steps include signal normalization to remove excessive noise from ambient lighting and patient motion from the AS7341. Signal detrending is also utilized for the analog sensors to remove baseline drift that occurs from variable pressure against the sensor and improve the accuracy of the cross-correlation. Both sensors sample at their optimal frequencies to achieve the greatest possible resolution.

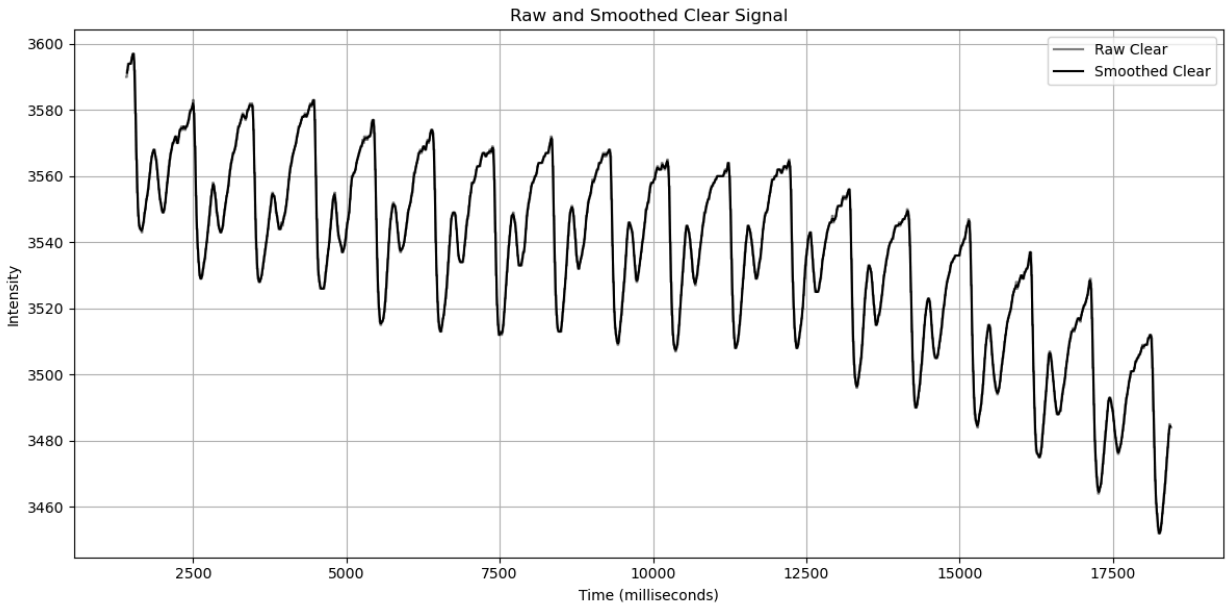

Figure 7. Pulse Signal in Clear Channel [Sample: Ricky Kanak]. In an individual pulse wave: the most prominent peak represents the systolic peak, the shorter neighboring peak represents the diastolic peak, and the dip in between these peaks is the dicrotic notch. For additional example, see Appendix C.

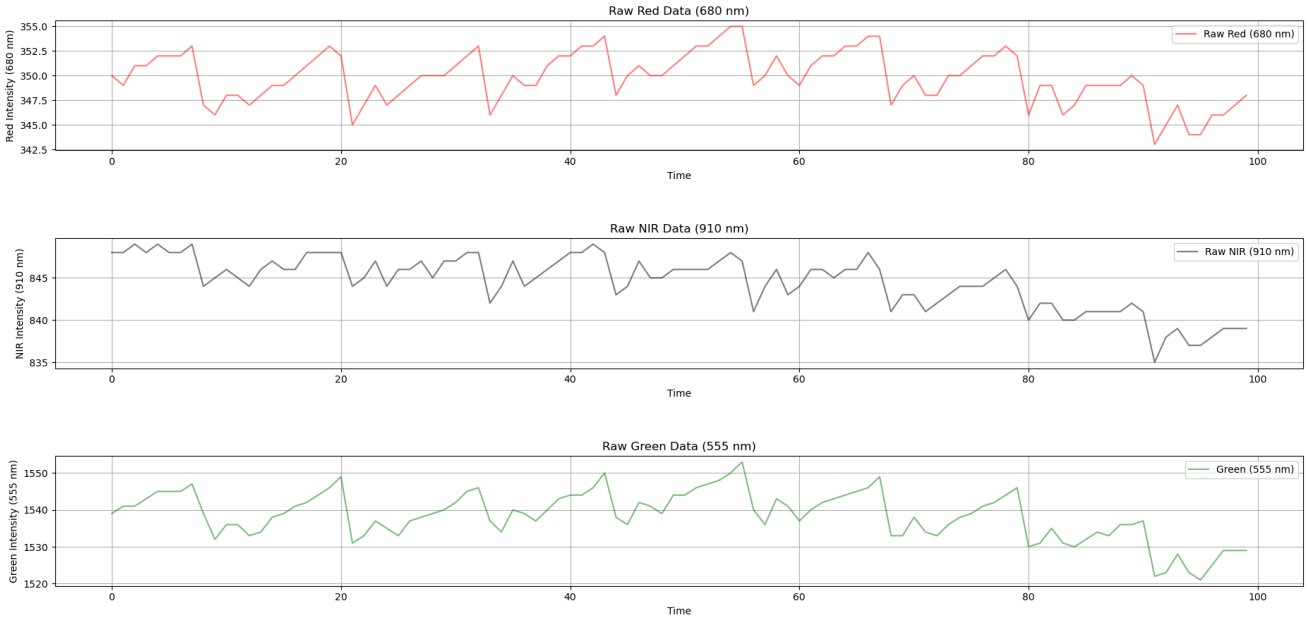

Figure 8. Transmission signal data displaying pulse reading in Red (680 nm), NIR, and Green (555nm) channels from AS7341. Intensity for red signal averages ~350 counts, NIR signal averages ~845 counts, green signal averages ~1535 counts. Ratio of Red:NIR is ~0.4. Time between readings: ~100ms. Note: Timestamps were not recorded, x-axis represents reading # index to model time - approximately in seconds.

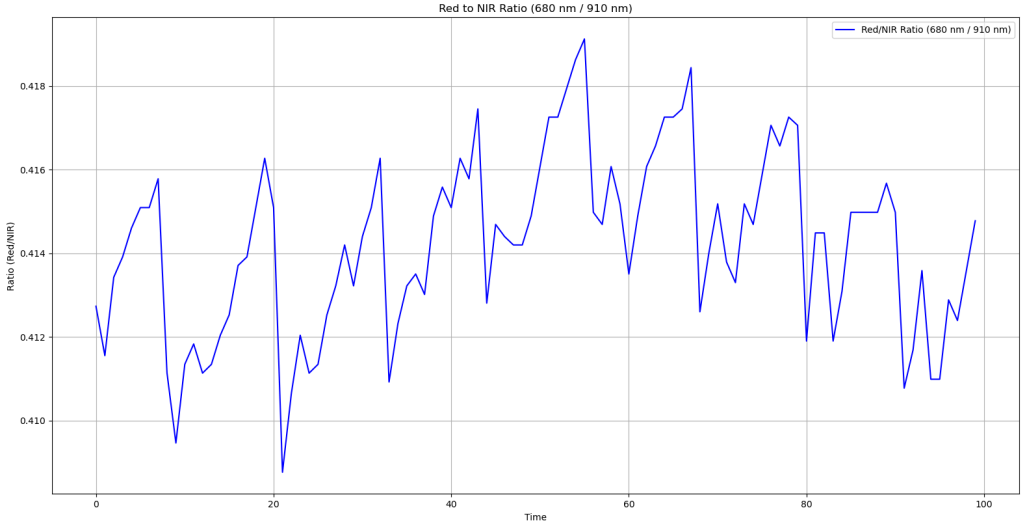

Figure 9. Ratio of Red (680 nm) signal to NIR signal. Ratio averages ~0.414, which corresponds with 99% SpO_2 measurement on commercial pulse oximeters. Time between readings: ~100ms. For additional ratio graphs, see Appendix D. Note: Timestamps were not recorded, x-axis represents reading # index to model time - approximately in seconds.

Measurement of intensity readings from the 680 nm and NIR channel readings (Figure 8) allows for the ratio of their transmission signals to be found (Figure 9). Oxygen saturation percentage (SpO_2) is determined from this ratio by finding the trendline of an SpO_2 versus ratio of red/NIR graph obtained from literature (Figure 2). The creation of these graphs is based on empirical data taken of oxygenation levels and the ratios of these wavelengths that describe them. However, due to these SpO_2 lookup tables not being accessible online the approach taken was to create a linear fit of the SpO_2 curve with select data points. This method was chosen because the SpO_2 versus red/NIR ratio curve is remarkably linear from 100% saturation to 60% saturation. Due to experimental limitations, calibration at low oxygen saturations cannot be achieved, and as such utilizing a linear fit which represents only a portion of the graph derived from empirical data is not an issue as is within the scope of the experiment and its capabilities.

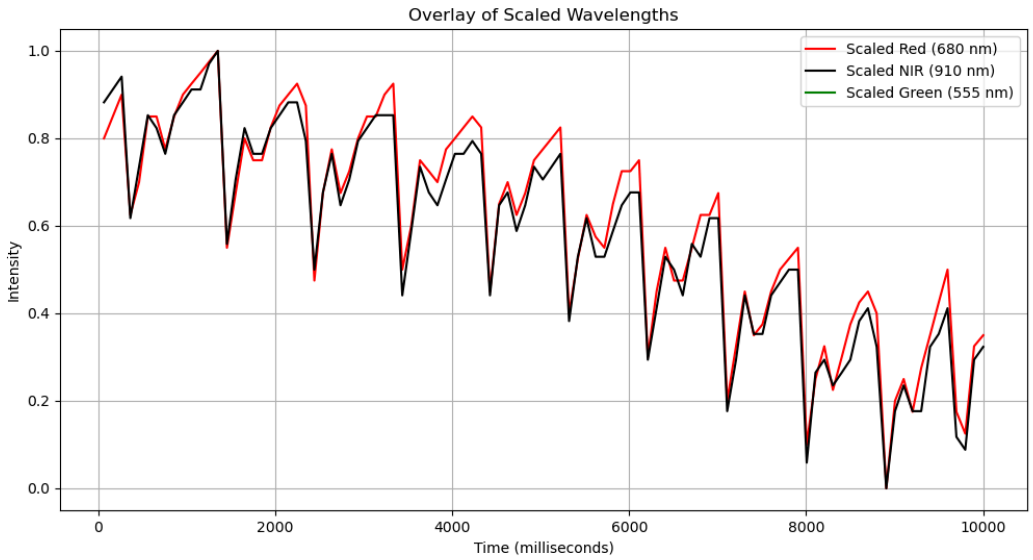

Figure 10. Overlay of scaled Red (680 nm) and NIR transmission signals for Deoxygenated Sample. The graph attempts to plot the Green (555 nm) signal as well, but the sensor was saturated with green light and the Green transmission signal flat-lined. Note the pronounced disparity in intensity between the peaks of the Red and NIR signal due to deoxygenation. For individually displayed signals, see Appendix E.

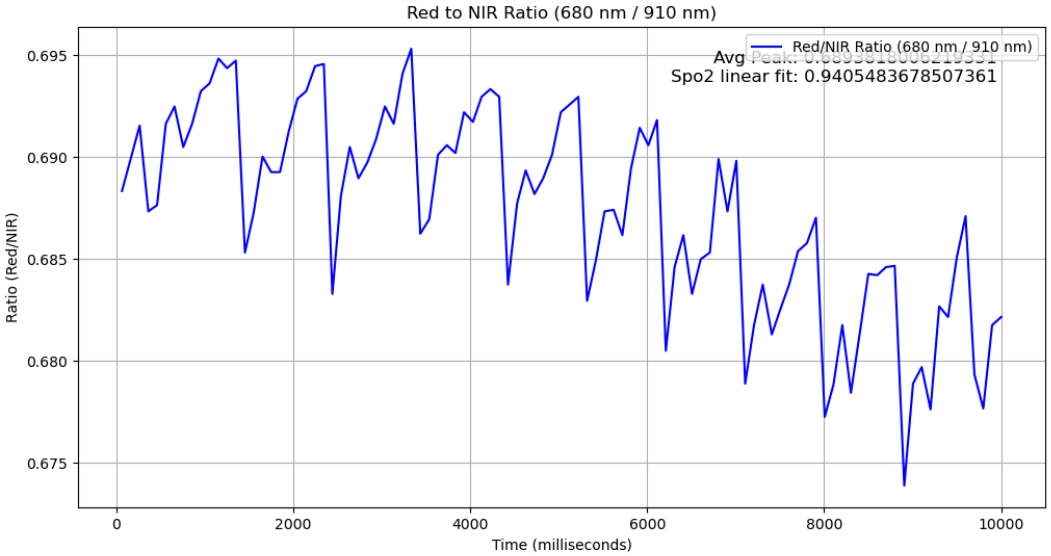

Figure 11. Ratio of Red (680nm) to NIR transmission signals. The average peak of the ratio graph is 0.69, with a calculated SpO_2 measurement of 94%. The commercial pulse oximeter used to verify accuracy of experimental measurements read 94% oxygenation as well.

(5) $$SpO_2 = -\left(\frac{76}{3}\right) * R_{Average} + 111.4$$

Deoxygenated samples were obtained by having a participant hold their brethren perform physical exercise such as running up a stairwell. Then a commercial pulse oximeter was attached to the index finger of the participant's left hand as readings with the AS7341 were taken with the right hand's index finger. Readings on both sensors were recorded and matched for three trials. A trial performed at 94% blood oxygenation produced a Red/NIR ratio of ~0.7 (Figure 11). Notably, tests performed at rest with commercial pulse oximeter readings of 99% oxygenation produced experimental ratios of ~0.4 (Figure 9). A trendline was obtained from Figure 2, resulting in equation (5) above. Inputting the average ratio into the equation yielded an SpO_2 calculation which matched the commercial pulse oximeter. This process was replicated in 2 subsequent trials and experimental SpO_2 measurements matched commercial readings. For these graphs and ratios, see Appendix E.

To assess the pulse transit time, ppg signals were recorded from both analog ppg sensors positioned 5 cm apart on the forearm. The proximal sensor was located closer to the elbow while the distal sensor was positioned nearer to the palm. These placements enabled a measurable delay in the systolic pressure wave propagation. The recorded measurements can be seen in Figure 12.

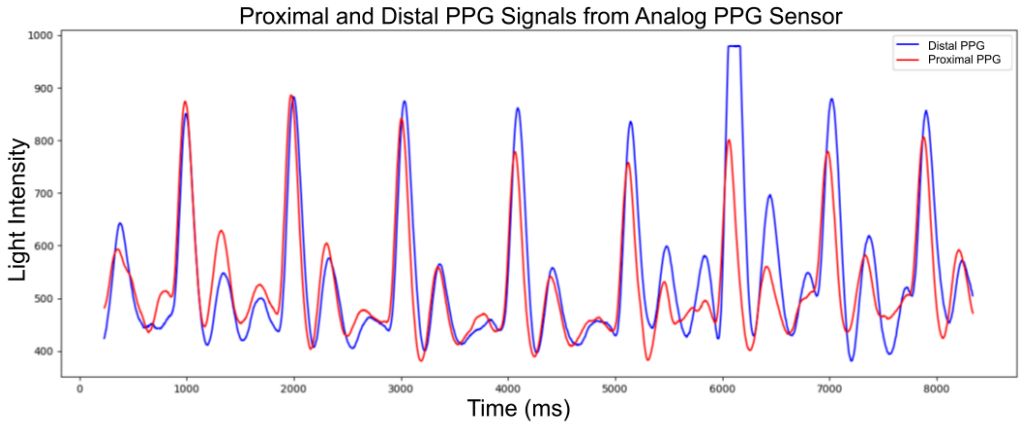

Figure 12. This graph of proximal (red) and distal (blue) PPG signals was recorded using analog sensors attached to Ricky's forearm 5 cm apart. The x-axis represents time (ms), and the y-axis represents light intensity. Notably, the proximal peaks precede the distal peaks corresponding to the pulse transit time.

The cross correlation function provides valuable insights into the relationship between proximal and distal PPG signals in the temporal domain. The cross-correlation of both signals shown in (Figure 12) exhibits a prominent peak at a lag of -5 milliseconds as shown in (Figure 13.) This lag indicates that the distal ppg trails the proximal by 5 milliseconds. Given that the sensors were positioned 5 cm apart, the PTT of the systolic pressure wave was calculated to be 10 m/s, consistent with the 5 m/s - 15 m/s range according to Pereira, Tânia et al, further validating our recordings and analysis procedures.

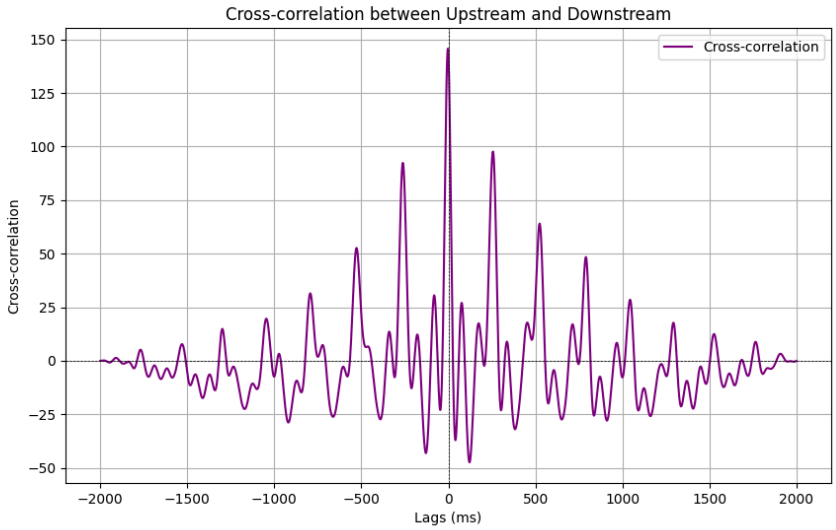

Figure 13. This graph of the cross correlation between proximal and distal PPG signals was used to measure the PTT. The lag in ms corresponding to the maximum cross-correlation value highlights the time difference between both signals.

6 Conclusions

This progress report outlines the development and optimization of a multi-sensor suite aimed at addressing disparities in blood oxygenation measurement due to variations in skin tone and potential developments to determine blood velocity and blood pressure from transmission signal data. Through the integration of AS7341 10-channel light sensors, analog pulse measurement sensors, and Arduino-based data analysis, significant advancements have been made in capturing reliable photoplethysmographic (PPG) signals and calculating SpO_2 values.

Key achievements include successfully implementing robust data collection techniques, validating initial SpO_2 measurements, and achieving a temporal resolution sufficient for pulse transit time (PTT) calculations. The complementary roles of the high-resolution analog sensors and the spectral versatility of the AS7341 sensors have positioned the project as a promising step towards developing comprehensive medical diagnostics. Early tests have demonstrated accuracy comparable to commercial pulse oximeters while highlighting areas for further refinement, such as improving data acquisition speed, optimizing sensor calibration, and mitigating artifacts caused by skin tone and motion.

6.1 Future Directions

Future work with the AS7341 setup includes collecting data samples from individuals with a variety of skin tones to calibrate transmission readings against a standardized baseline. This calibration will enable color correction for oxygenation measurements derived from the red/NIR ratio method. To achieve accurate SpO_2 readings, a robust and reliable method for analyzing the red/NIR transmission ratio must be developed, facilitating precise derivation of blood oxygenation levels from SpO_2 reference charts. Additionally, exploring the alternate ratio based on AC/DC readings could prove valuable in mitigating artifacts and discrepancies caused by skin tone variations and other external factors.

Consistent pulse signals have been achieved as well as rudimentary pulse oxygenation (SpO_2) measurements. These measurements will be further refined through development of more thorough trend lines to define the relationship between the ratio of red to NIR transmission signals and improve accuracy of measurement, attempting to reduce noise by utilizing the “ratio of ratios” method discussed earlier, and increasing data acquisition speed and resolution through reading individual channels to obtain transmission signals.

Immediately before Fall break, we accurately captured PPG signals from both pairs of sensors and saved the information to an SD card for analysis in Python. Currently, we are working on transitioning our data analysis procedures from Python to the M4 Feather so the apparatus can function autonomously. Simultaneously, we will work on the physical orientation of the sensors, custom PCB, and mechanism to secure the device to the patient.

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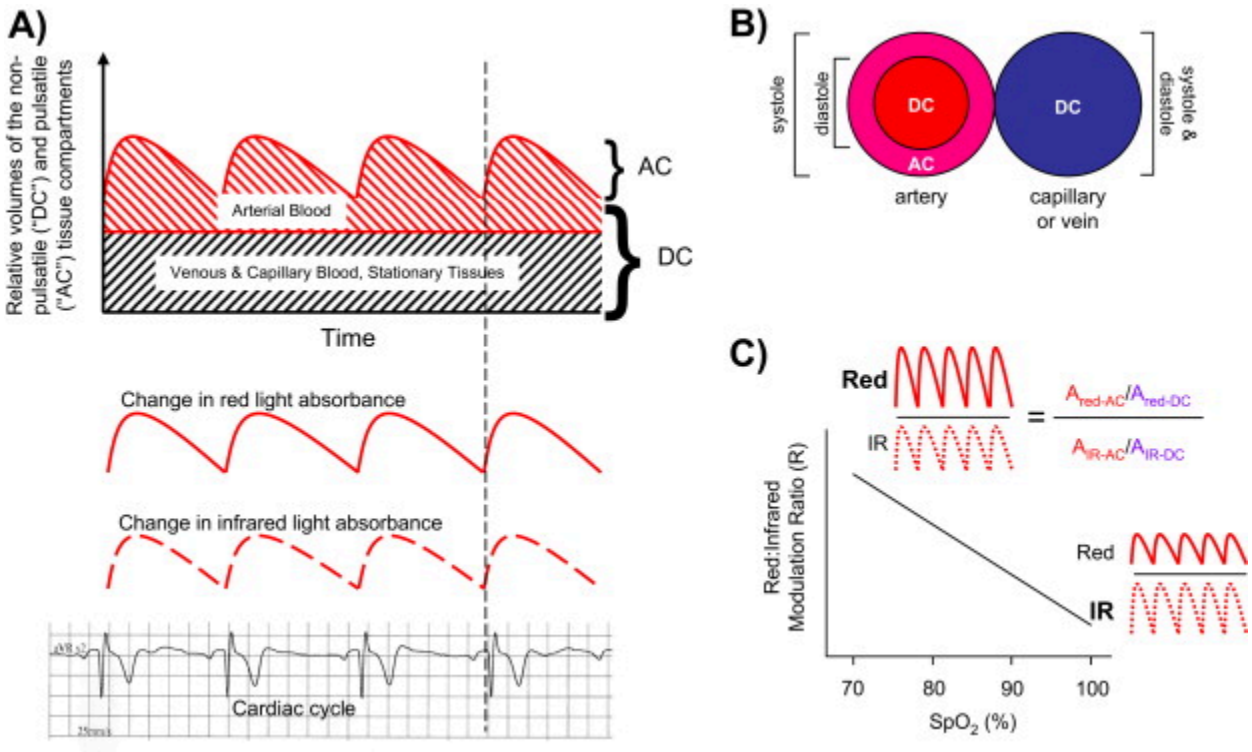
Appendix

Appendix A: Additional SpO_2 figures (Chan et al.)



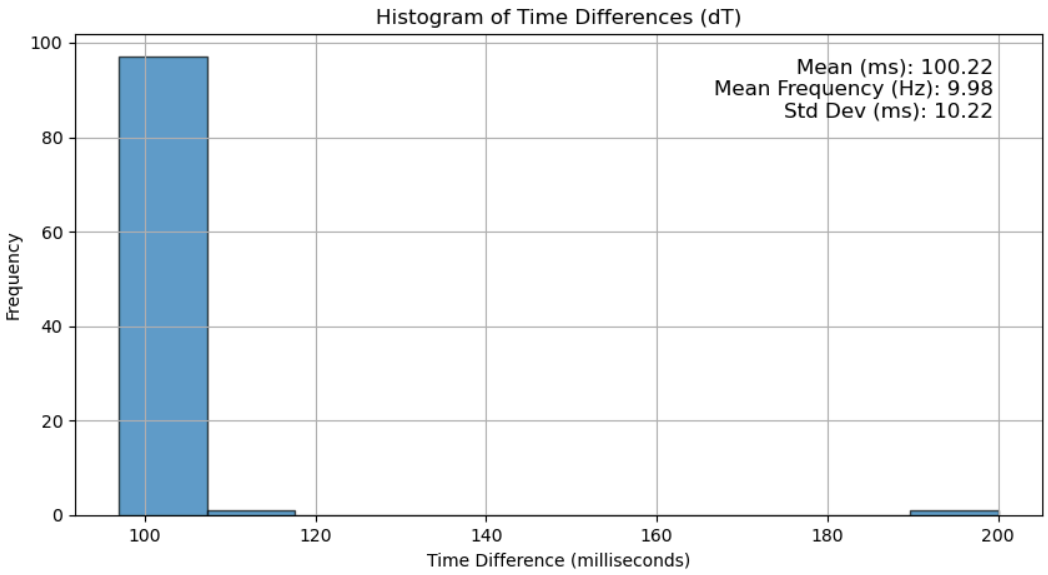
AC/DC normalization to prevent artifacts (Ratio of ratios).

(A) The AC component is mainly composed of fluctuations in the volume of arterial blood, while the DC component comprises absorbance/transmission signal components caused by dispersion in the capillaries and stationary tissues. Taking the ratios of AC signal for red (680 nm) light and NIR light accounts for the ratio of absorbance/transmission of primarily arterial blood.

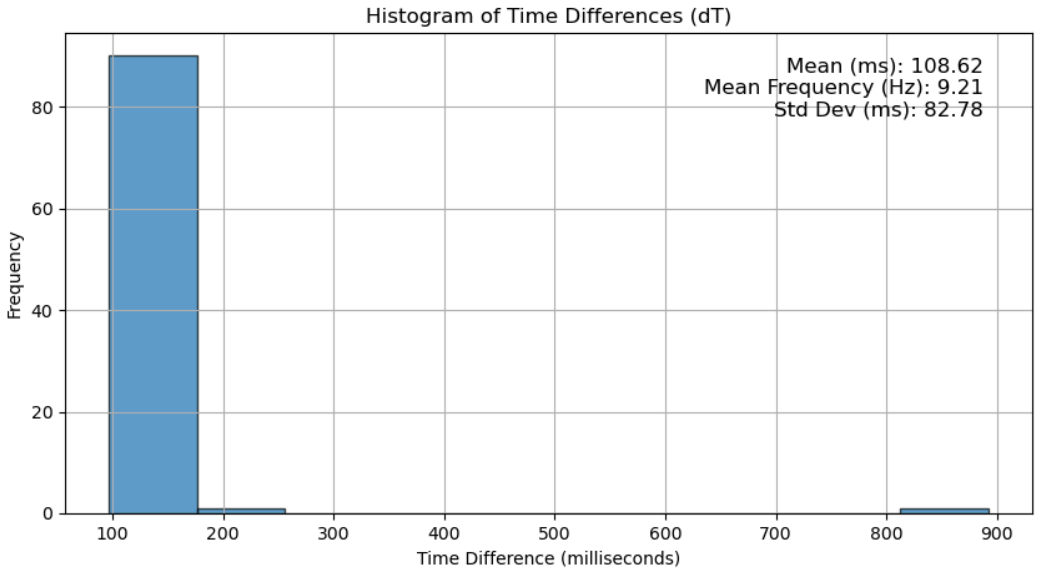
(B) Both diastole and systole contribute to the absorbance/transmission signal to form a pulse measurement. Diastole (heart relaxation) contributes primarily to the DC component of the absorbance/transmission signal, with some AC contribution as well. Systole (heart contraction) contributes the majority of the AC component of the absorbance/transmission signal.

(C) The ratio of the AC component to the DC component of the absorbance/transmission signal of red light over that of NIR/IR light (a "ratio of ratios") can be used to determine the oxygen saturation (SpO_2) of a sample.

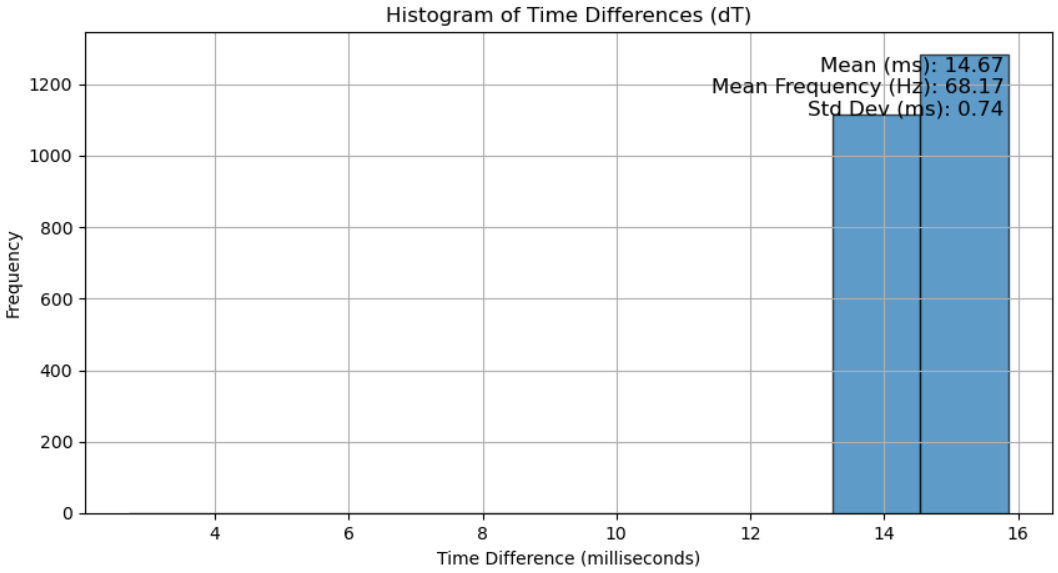
Appendix B: Additional histograms describing AS7341 measurement time resolution



Histogram (2) showing the distribution of time differences between subsequent transmission intensity measurements recorded using the readAllChannels setting on the AS7341 sensors. The mean time difference is 100.22 ms, with a standard deviation of 10.22ms. The corresponding mean frequency of measurements is 9.98 Hz.

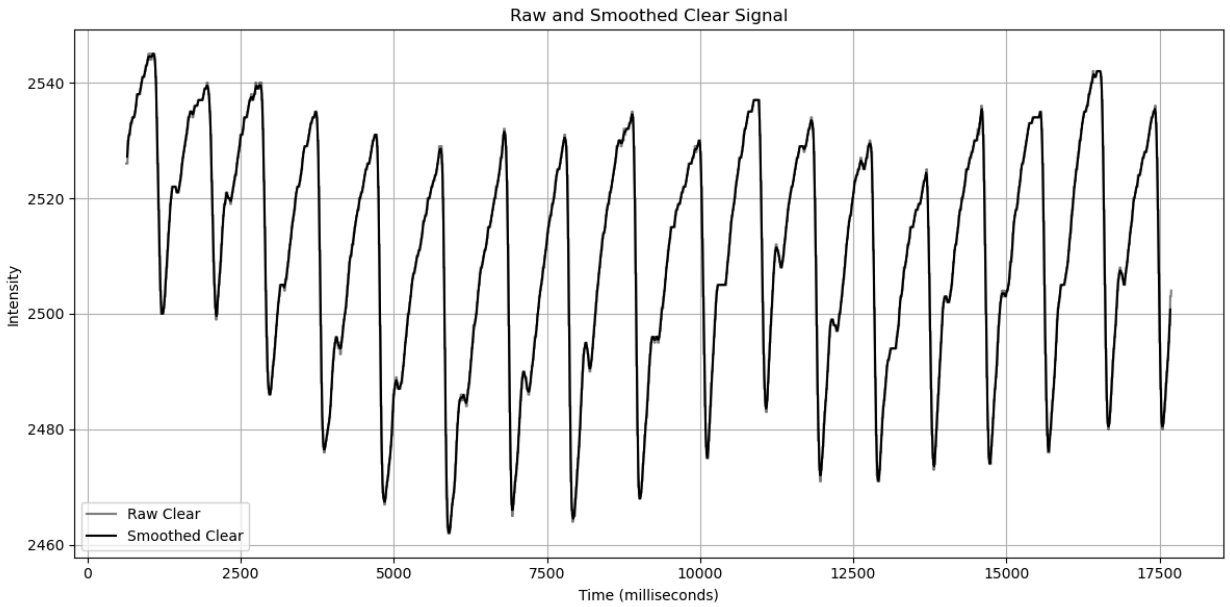


Histogram (3) showing the distribution of time differences between subsequent transmission intensity measurements recorded using the readAllChannels setting on the AS7341 sensors. The mean time difference is 108.62 ms, with a standard deviation of 82.78ms. The corresponding mean frequency of measurements is 9.21 Hz.

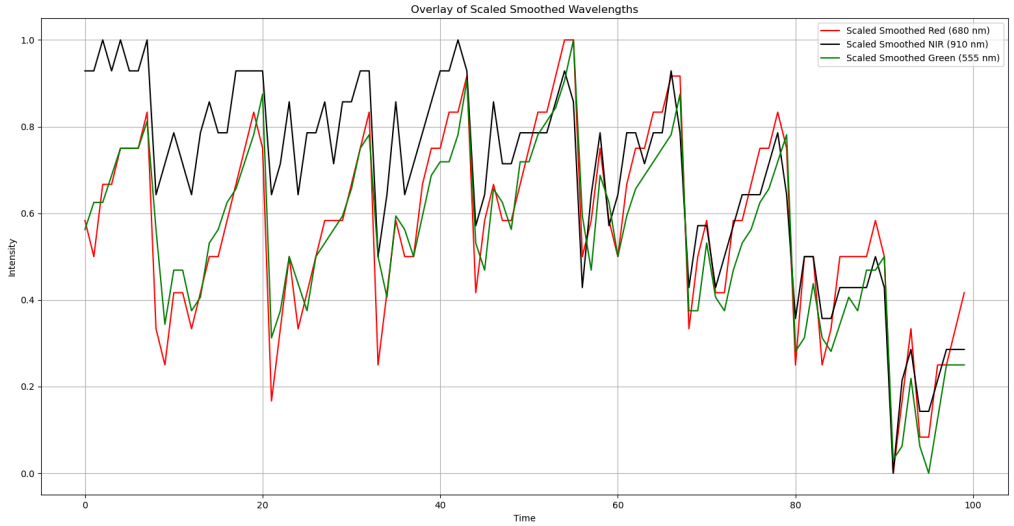


Histogram (4) showing the distribution of time differences between subsequent transmission intensity measurements recorded from an individual channel with readChannel and delayForData settings on the AS7341 sensors. The mean time difference is 14.67 ms, with a standard deviation of 0.74 ms. The corresponding mean frequency of measurements is 68.17 Hz.

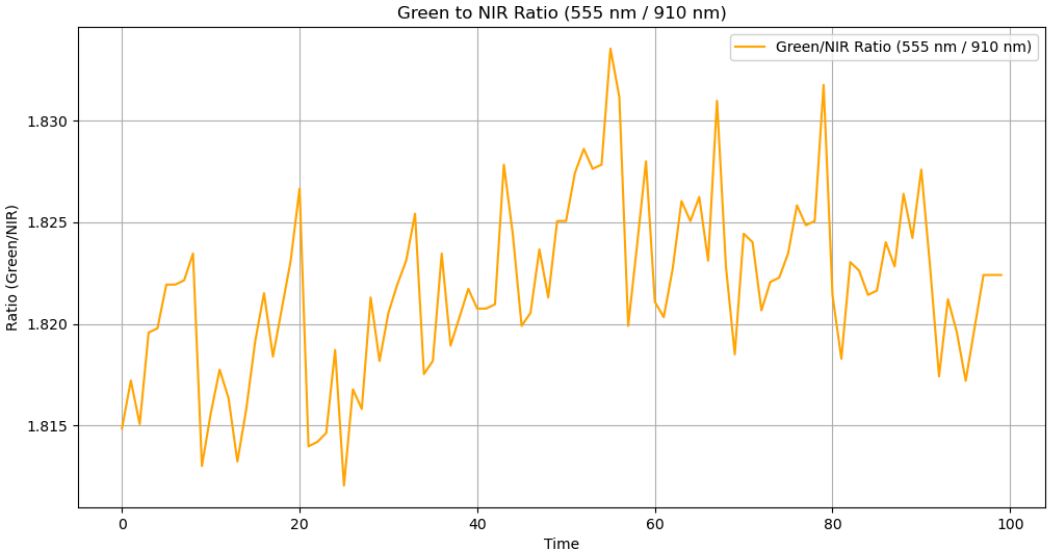
Appendix C: Additional pulse graph signal in clear channel [Sample: Leron Maddi]



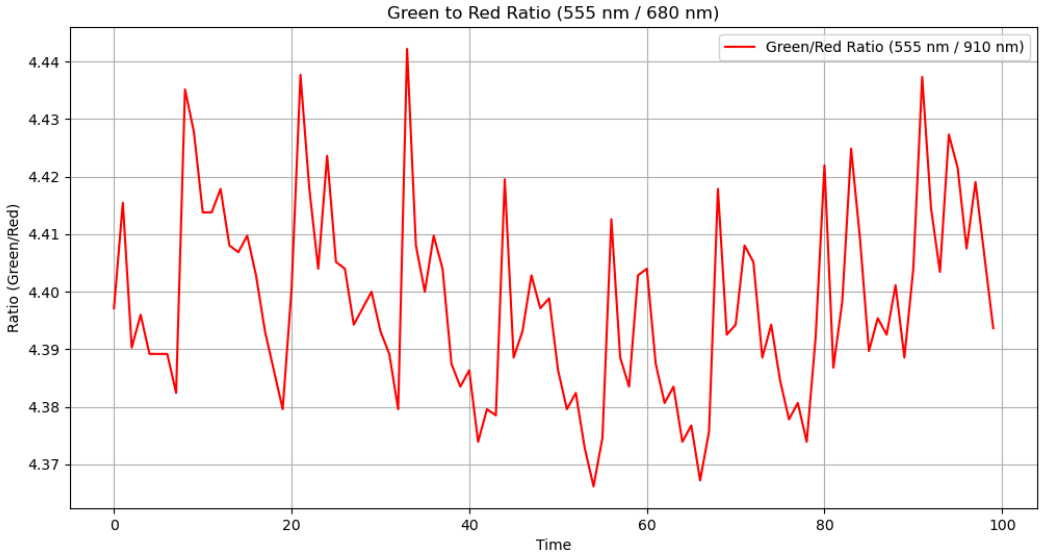
Appendix D: Supplementary ratio and raw signal graphs for Figure 8 and Figure 9



Overlay of transmission signal from Red (680 nm), NIR, and Green (555 nm) channels on AS7341 10-channel Sensor. Time axis approximately in seconds.

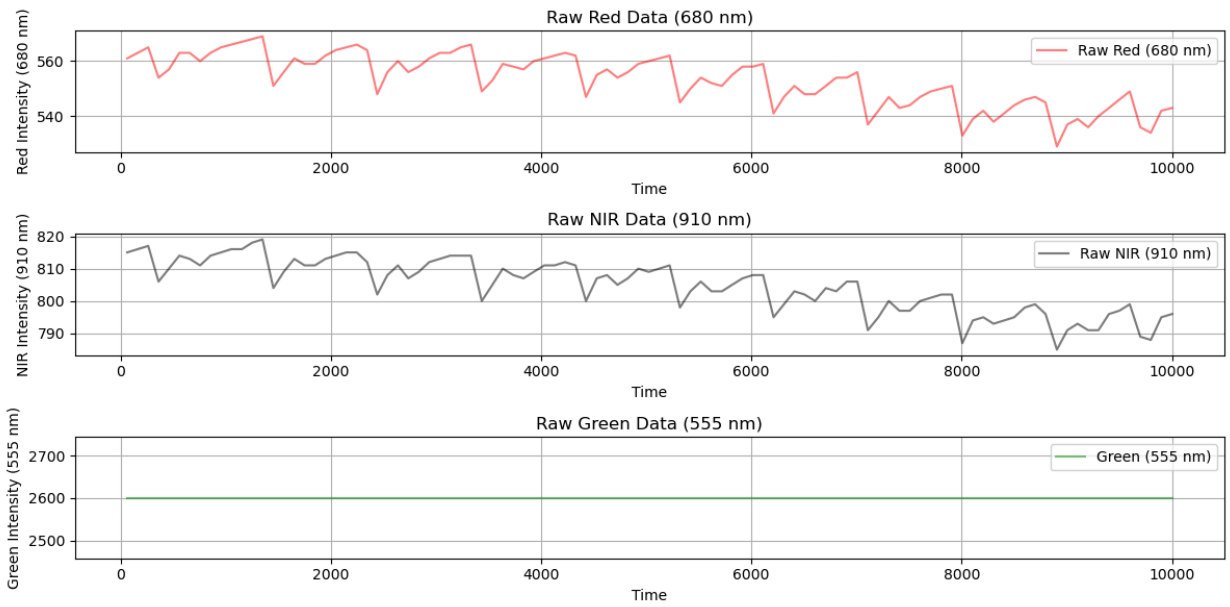


Ratio of Green (555 nm) to NIR transmission signals. Ratio averages ~1.82. Time axis approximately in seconds.

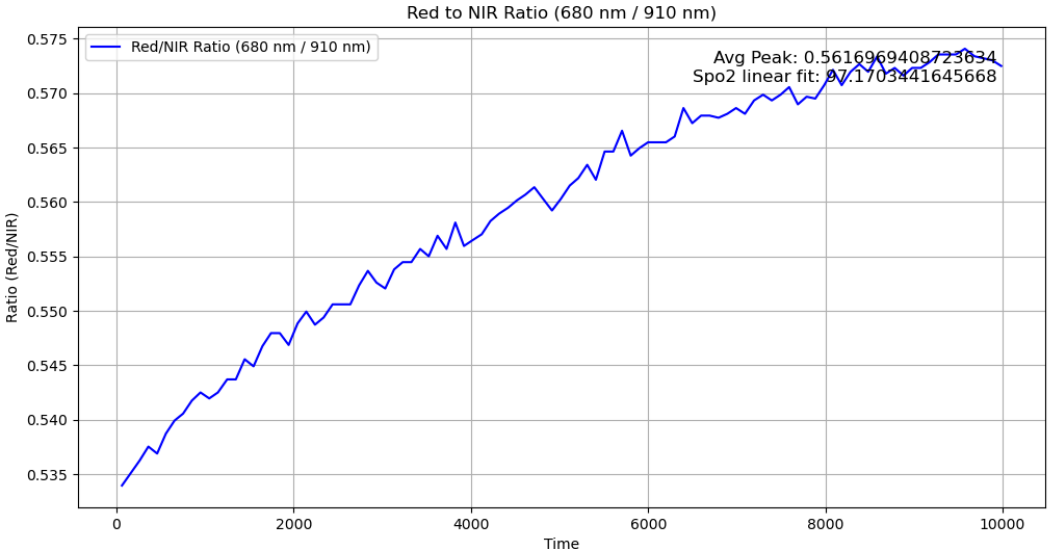


Ratio of Green (555 nm) to Red (680 nm) transmission signals. Ratio averages ~4.4. Time axis approximately in seconds.

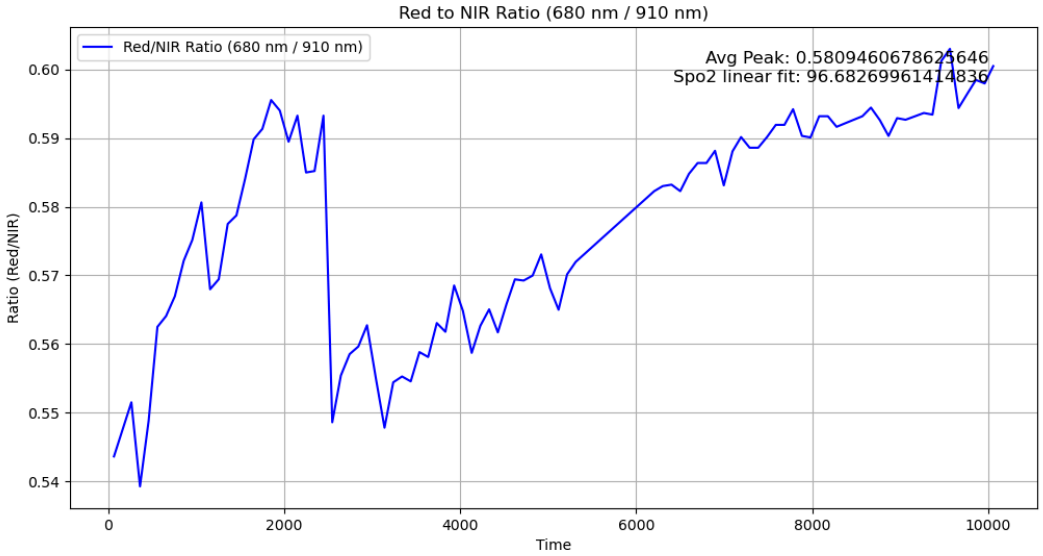
Appendix E: Additional Deoxygenated SpO_2 Calibration Results



Raw transmission signals for Red (680 nm), NIR, and Green (555 nm). Note: Green signal saturated sensor at max intensity of ~2600 counts. Time in milliseconds. Corresponds to Figure (10).

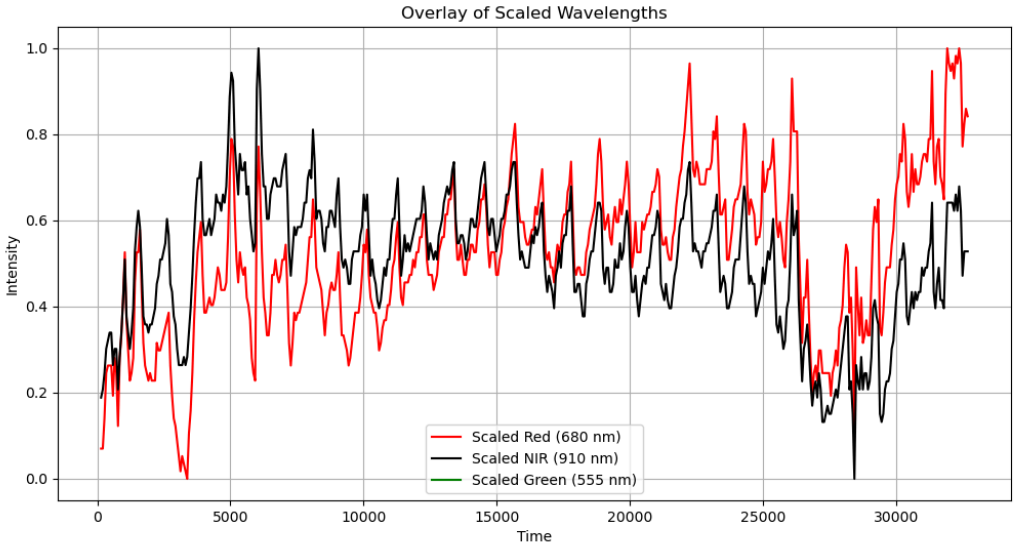


Ratio of Red (680 nm) to NIR transmission signals (2). The average peak of the ratio graph is 0.56, with a calculated SpO_2 measurement of 97%. The commercial pulse oximeter used to verify accuracy of experimental measurements read 97% oxygenation as well. Time in milliseconds.

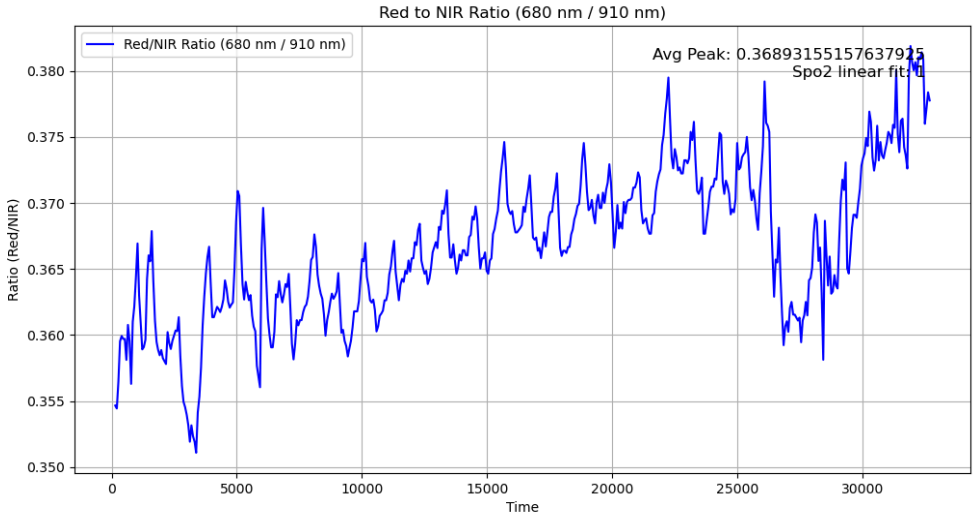


Ratio of Red (680 nm) to NIR transmission signals (3). The average peak of the ratio graph is 0.58, with a calculated SpO_2 measurement of 97%. The commercial pulse oximeter used to verify accuracy of experimental measurements read 97% oxygenation as well. Time in milliseconds.

Appendix F: Extra Red (680 nm) and NIR transmission signals and ratio graphs from older dataset.

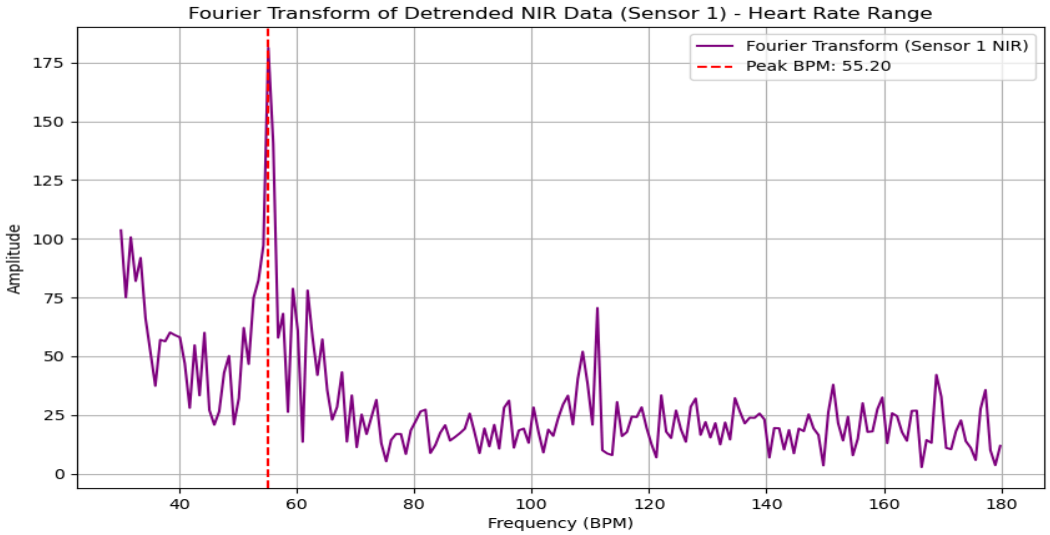


Extra pulse graph with 680 nm and NIR signals over a longer period. Time in milliseconds: 30 seconds total.



Corresponding Red (680 nm) to NIR signal ratio. Average ratio ~0.37, SpO_2 ~100%. Time in milliseconds: 30 seconds total.

Appendix G: Heart rate determination through Fourier Analysis.



Heart rate of 55.20 BPM determined through Fourier transform of transmission signal.

Subject's true heart rate determined through a commercial pulse oximeter was 55 BPM.