Application Report
SLAA655–March 2015

How to Design Peripheral Oxygen Saturation (SpO_2) and Optical Heart Rate Monitoring (OHRM) Systems Using the AFE4403

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ABSTRACT

Pulse Oximeters in clinics have a finger clip type probe that has an LED on one side and a photo detector on the other side. The light emitted from one side of the finger travels through tissue, venous blood and arterial blood and is collected in the detector. Most of the light is absorbed or scattered before it reaches the photo detector in the other side of the finger. The flow of blood is heartbeat induced, or pulsatile in nature so the transmitted light changes with time. Red and infrared lights are used for pulse oximetry to estimate the true hemoglobin oxygen saturation of arterial blood. Oxyhemoglobin (HbO2) absorbs visible and infrared (IR) light differently than deoxyhemoglobin (Hb), and appears bright red as opposed to the darker brown Hb. Absorption in the arterial blood is represented by an AC signal which is superimposed on a DC signal representing absorptions in other substances like pigmentation in tissue, venous, capillary, bone, and so forth. Cardiac-synchronized AC signal is approximately 1% of the DC level. This is referred to as the perfusion index %. The ratio of ratios 'R' is approximated in Equation 1. % SpO_2 is calculated as follows:

$$R = (ACrms\ of\ Red / DC\ of\ Red) / (ACrms\ of\ IR / DC\ of\ IR) \quad (1)$$

The standard model of computing SpO_2 is defined as shown in Equation 2. This model is often used in the literature in the context of medical devices. However, accurate % SpO2 is computed based on the empirical calibration of the ratio of ratios for the specific device.

$$\%\ SpO_2 = 110 - 25 \times R \quad (2)$$

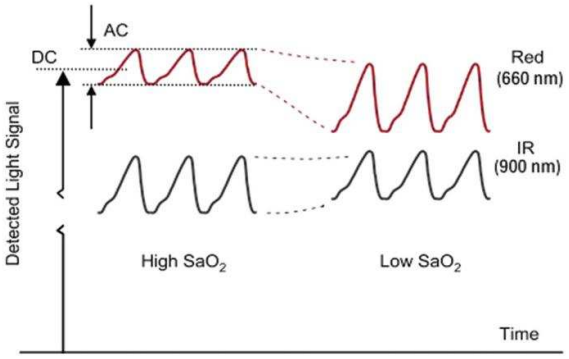


Figure 1. Red and Infra Red Modulated by Cycling Blood

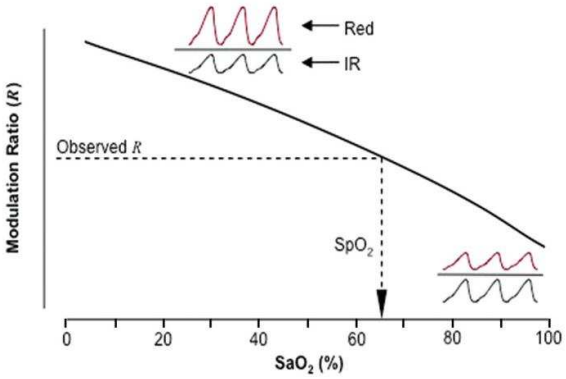


Figure 2. Red/Infrared Modulation Ratio

This document does not go into the details of the SpO_2 calculation, instead, it discusses the key considerations on how to obtain a good quality PPG signal. The PPG signal can also be used to extract the heart rate information. Advanced applications with the PPG signal include vascular age, arterial stiffness index, and so forth. Irrespective of the target application, understanding the characteristics of light traveling through human body tissue is very important before one designs an LED lighting and photo detector module fitting into a given space and location. With mobile phones or wearable applications, there are also special constraints in space.

1 PPG Signal Acquisition

The optical system for SpO_2 measurement consists of LEDs that shine the light and a photodiode that receives the light. There are two types of optical arrangements – Transmissive and Reflective. In the transmissive case, the photodiode and the LED are placed on opposite sides of the human body part (most commonly the finger), with the photodiode collecting the residual light after absorption from the various components of the body part. In the reflective case, the photodiode and the LED are on the same side and the photodiode collects the light reflected from various depths underneath the skin. With the conventional finger clip type probes commonly seen in a clinic, one could simply imagine that the emitted light from the LED goes straight through the tissue, interacts with blood cells somehow and continues to travel in the same direction until it reaches the photodiode, or photo detector (PD). This is not the case. Photons in the light scatter in every direction when it hits an object, for example, blood cells. LED and PD separation in the finger clip probe is around 10 mm. However, most of the photons travel 20 cm to 10 cm before reaching the PD. Some travel as long as 200 mm. The photons could be described as walking randomly. This is why glow is seen in the skin of the finger tip in Figure 3. If the light traveled in the straight path, that is the shortest one, how could the surrounding skin of the finger glow so bright? Since we have gotten out of the old belief that the emitter and detector have to face each other, we can try placing them in easier directions like side-by-side or even at 90 degrees.

For a fair comparison between the transmissive case and reflective case, the finger clip was used for the transmissive case measurement and for the reflective case, the plastic casing was disassembled into tiny silicon rubber moldings of LED and PD. On top of the chips were transparent silicon rubber windows preventing direct contact with the skin. With this method, only the casing designed to block ambient light was removed. The AFE4403EVM GUI was used to capture the PPG Waveform. For the finger clip measurement, the DC level is about 93 mV. The AC swing is shown about every 500 samples which corresponds to around 1 second of heartbeat spacing. One sample time is set at 2 ms. Note that the thick line that overrides on the main swing is 60-Hz AC noise. The laptop for the EVM is powered by the AC-DC adaptor. Without it, the USB port had trouble transferring data between the GUI in the laptop and the EVM. Key factors are AC swing and DC level. AC swings in both sensor locations are measured the same 0.04 V, or so. Very strong AC swing is noted even in the side-by-side sensor location. One of the reasons for the large DC value in the reflective case is due to a large number of photons hitting the photodiode directly from the emitter before being absorbed inside the tissue or interacting with blood. The periodicity of the PPG signal corresponds to the heart rate.

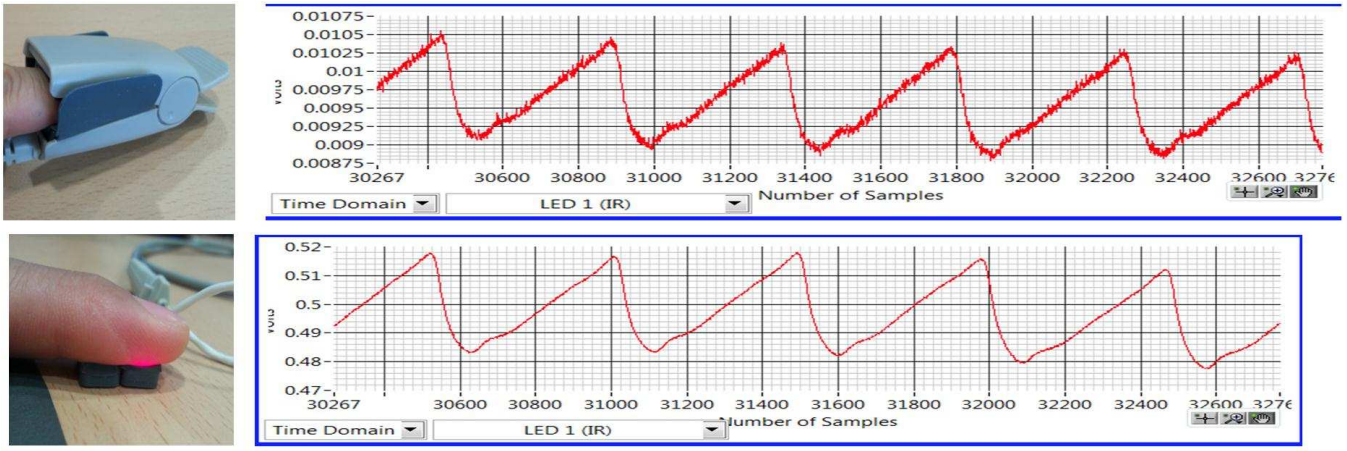


Figure 3. PPG Signal Acquisition From Transmissive Versus Reflective Sensors

The electrical current from the photo detector is in the order of nano-amperes. Since the output current of the PD is very small, an analog front end (AFE) is required to perform signal amplification and digitization of the photodiode output. The AFE4403 signal chain offers several knobs such transimpedance amplifier (TIA) gain, ambient light compensation, additional stage 2 gain, and LED current that can be adjusted to achieve the SNR requirements needed for high-end clinical pulse oximeter applications as well as the low power demands of battery-powered OHRM applications.

Figure 4 illustrates the PPG signal at two different LED current settings. This figure helps us to understand the detected light versus the absorbed light of the PPG signal at different LED current settings. An understanding of the characteristics of the PPG signal is essential to configure the AFE with the optimum gain and LED current settings.

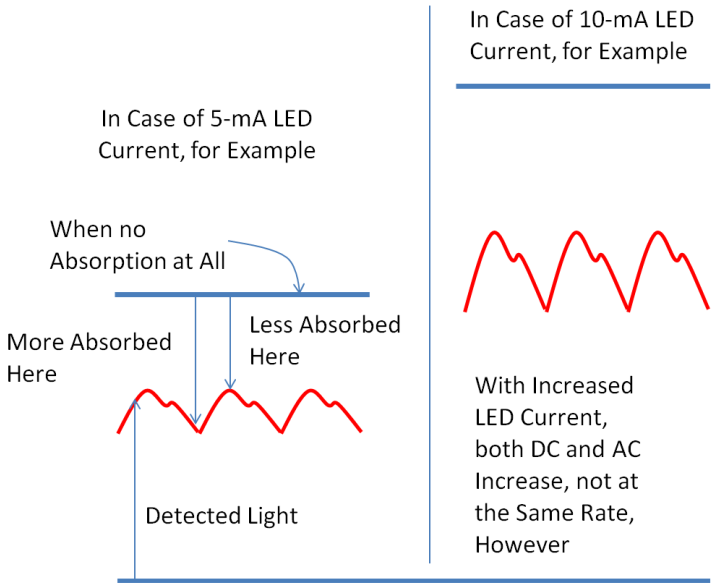


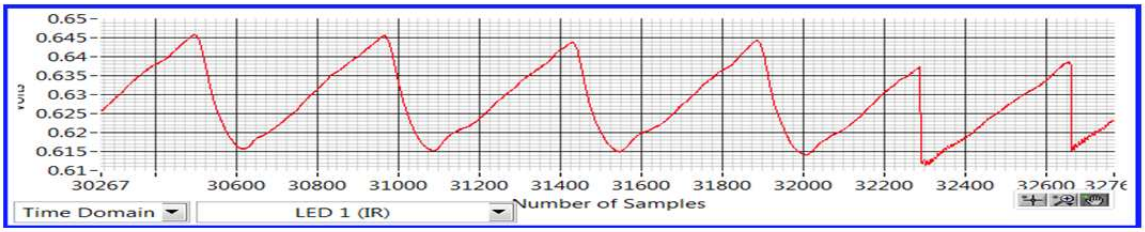
Figure 4. Sketch of PPG to Help Conceptual Understanding of Detected Light vs Absorbed Light

A green LED has often been used in the reflective sensor to extract the PPG signal. Due to its wavelength, green light is known to penetrate the tissues less than higher wavelength LEDs. Hence, more unabsorbed (reflected) light comes out of the tissue with green than with other colors. Sensing the green light from more than one PD or eliminating from more than on LEDs surrounding the PD helps. Since green LEDs have higher Vfb, a DC/DC boost converter is usually required to derive the supply voltage for the LED driver.

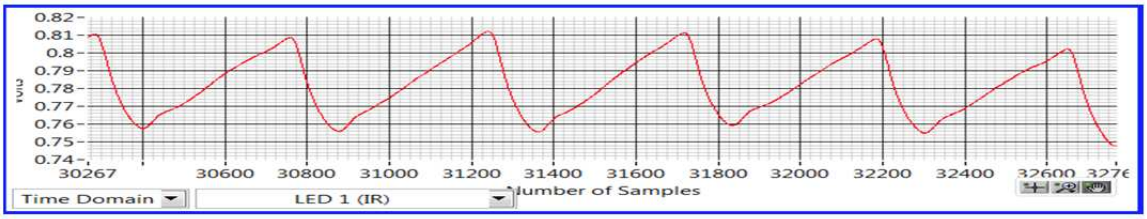
2 LED Current and TIA Gain Impact to the PPG Signal

As mentioned earlier, AFE4403 has several knobs to control but for power versus performance tradeoffs, LED current and TIA gain are the two major knobs used to achieve optimum performance. Averaging and post processing of the PPG signal after the ADC also provide more alternatives; however, this is beyond the scope of this document. For the best ADC performance under the most challenging conditions, TI recommends operating the ADC at 50% of ADC full scale. This margin allows for sudden changes in the PPG signal due to high ambient light and motion artifacts. To maintain the DC at 0.6 V, either LED current or TIA gain can be increased. Amplification of the incoming signal is also vulnerable to the SNR performance in the amplifier because noise also gets amplified inevitably. There is a second stage amplifier following the TIA. Turning on the second amp to get 6 dB, for example, consumes around an extra 100 µA. This is not a significant loss of power when we compare with an alternative where we double the LED current to double the DC. However, increasing the LED current gives better signal quality from the SNR perspective. The optimal AFE configuration settings are completely dependent on the application. This includes the separation of LED and PD, location of the sensor, and other factors.

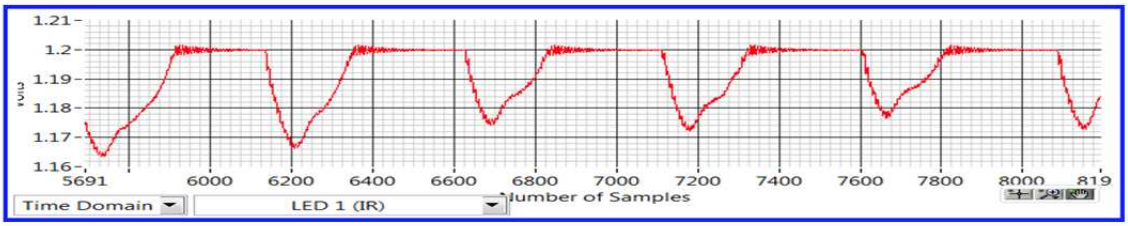
Figure 5 illustrates the change in the DC and AC signal with the change in LED current. As seen from Figure 5, increasing the LED current increases the DC level of the PPG signal. Figure 5c presents a case where very high LED current can also saturate the PPG signal. Figure 6 illustrates the impact of TIA gain on the PPG signal. Increasing the TIA gain increases the DC level of the PPG signal.



a) LED Current at 5 mA

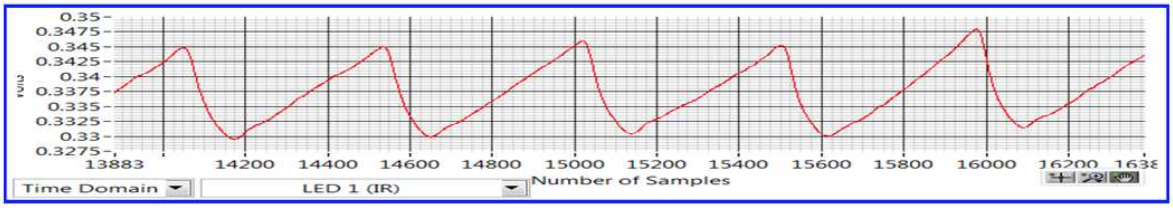


b) LED Current at 10 mA

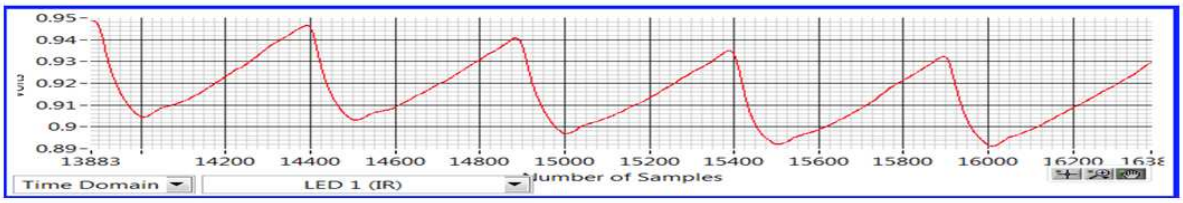


c) LED Current at 20 mA. High End is Saturated in the ADC

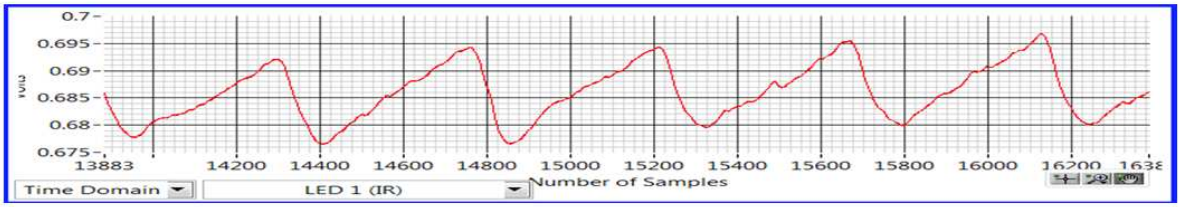
Figure 5. Impact of LED Current on the PPG Signal



a) 250-kΩ TIA Gain



b) 500-kΩ TIA Gain



c)250-kΩ TIA Gain Followed by 6-dB Amp

Figure 6. Impact of Gain on the PPG Signal

3 Calibration of LED Current and TIA Gain

The light absorption level of the tissues varies for different users. Also the light absorption level of the tissues varies in time for the same user. Hence, the same LED current and gain settings of the AFE4403 will not work for all users. To optimally use the full dynamic range provided by the AFE4403 signal chain, it becomes imperative to implement a gain and current calibration routine. The calibration routine can start with initial settings for the various parameters and dynamically figure out the most optimal settings under varying conditions. As for battery-powered HRM or SpO_2 application using AFE4403, TI suggests setting the DC target threshold at about 30% of ADC full scale range. Figure 7 illustrates the execution of the calibration routine adjusting the TIA gain and the LED current to achieve the target threshold DC value of 40% of ADC full scale. The calibration operation begins with the initial configuration of 1 MΩ of TIA gain and the lowest LED current allowed for the application (5 mA in this example). The DC level is measured and since the DC value is greater than the target threshold, the TIA gain is reduced until the target threshold is achieved. If the DC value is less than the target threshold then the LED current is increased to achieve the target threshold.

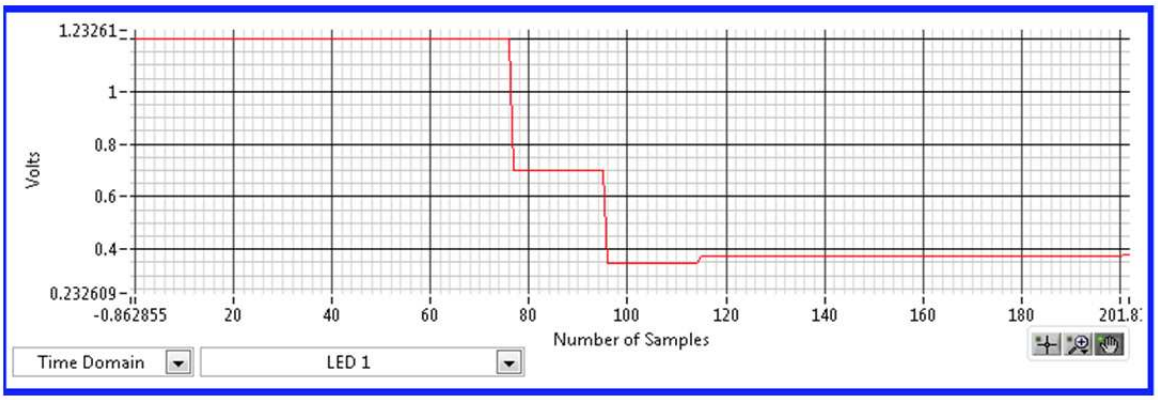


Figure 7. Calibration Routine Showing Change of Voltage Based on the TIA Gain and LED Current Settings

4 Post Processing

Each time the ADC_RDY signal interrupts the main processor, the processor accesses the AFE4403 through the serial peripheral interface and reads out the ADC registers. We have observed the power line noise and other motion artifacts getting coupled to the PPG signals reducing the SNR drastically. For HRM applications, it is imperative to remove the noise and baseline drift. Heart rate estimation usually requires an algorithm that filters the noise and detects the beat-to-beat heart rate and average heart rate. Even under rest conditions, the extraction of heart rate can get complicated due to the sudden changes in the DC level of the signal due to respiration and motion artifacts. The heart rate can be calculated by measuring the separation between the successive peaks of the signal after eliminating the effect of the sudden DC level shifts. In the presence of artifacts such as motion, the PPG signal can be buried under these artifacts. This requires motion cancellation algorithms, usually aided by data from accelerometers to be able to remove the motion artifact and extract the heart rate. Figure 8 presents the filtered data after post processing.

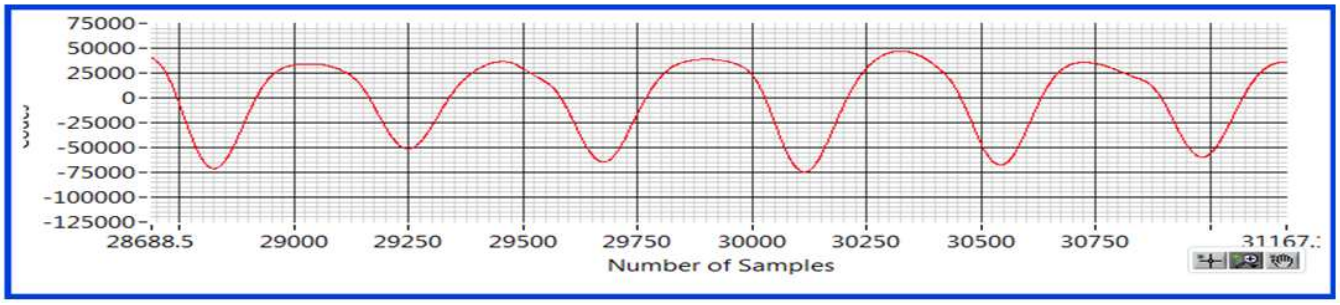


Figure 8. Filtered PPG Waveform After Post Processing (Band-Pass-Filtering)

4.1 References

1. *The Light-Tissue Interaction of Pulse Oximetry*: by Paul D. Mannheimer, PhD., December 2007.
2. *Pulse Oximeter Fundamentals and Design*: by Santiago Lopez, September 2011

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