Recommended Configurations and Operating Profiles for MAX30101/MAX30102 EV Kits

UG6409; Rev 0; 3/18

Abstract

This user guide was developed to help users quickly configure the MAX30101 and MAX30102 devices for pulse-ox and/or heart-rate monitoring use using the MAX30101ACCEVKIT and MAX30102ACCEVKIT. Recommended operating profiles are offered as well as a suggested methodology for determining signal optimization and associated power-supply requirements. In addition, heart-rate and pulse-ox calculation examples are given that are representative of basic post-processing operations.

Table of Contents

List of Figures

Introduction

This user guide presents heart-rate and SpO2 configurations for the MAX30101/MAX30102 (MAX3010x) product family evaluation kits. The MAX3010x provides a complete optical-module solution to ease the design-in process for mobile and wearable devices for both fitness and health. Because the MAX30101 and MAX30102 work similarly, with the only difference being the LEDs present (see Table 1), this user guide focuses on the MAX30101 device throughout. The user should be aware that the same settings can be applied to MAX30102 devices. Additionally, MAX3010x EV kit boards (MAX30101ACCEVKIT and MAX30102ACCEVIT) also feature an ultra-low-power linear accelerometer that can be used to implement motion detection or compensation algorithms.

Table 1. MAX3010x Product Family and Their Available Modes

DEVICE	LEDs PRESENT	AVAILABLE MODES
MAX30101	Green, Red, Infrared	HR, SpO2
MAX30102	Red, Infrared	HR, SpO2

Pulse Oximetry and Heart Rate

Pulse oximetry is a noninvasive method of measuring an individual's blood oxygen saturation levels. Oxygen saturation levels, referring to the ratio of oxygenated hemoglobin to total hemoglobin in the blood, can aid in detection of hypoxemia, deteriorating organ function and even cardiac arrest. Therefore, a noninvasive solution to measure oxygen saturation levels, as provided by MAX3010x, is of medical importance. Additionally, there is an inherent heart-rate signal associated with pulse-oximetry measurement, allowing the MAX30101 users to obtain this as well.

Transmissive Pulse Oximetry

LEDs transmit light of specific wavelengths through tissue, which is absorbed by photodetectors on the other end. The change in absorbance of each wavelength determines oxygen saturation levels. This application requires use of a thin test site with adequate blood perfusion like a finger or ear lobe to maximize the transmission of light.

Reflective Pulse Oximetry

In this case, the setup is like the one used for transmissive pulse oximetry except the photodiodes are placed on the same side of the test site as the LEDs. The LED light illuminates the skin while the reflected signal is monitored for changes in light absorption. This is known as photoplethysmography (PPG): the optical measurement of organ volume changes. In the same way, the MAX30101 monitors the perfusion of blood to the dermis and subcutaneous tissue of the skin. Reflective pulse oximeters work well for many mobile fitness applications as the technology is independent of tissue depth, unlike the transmissive method. The MAX3010x product family uses reflective pulse-oximetry technology to determine HR, and SpO2.

Note: *Each type of pulse oximetry method relies on the idea that the light reflected or transmitted from the tissue is a signal strong enough to be captured by the photodiode. Thus, depending on the application MAX3010x is used for, the LED signal strength, pulse width, or sampling rate needs to be changed by the user to optimize its performance.*

Primary Applications

- SpO2 Operation
- Heart-Rate Monitoring
- Proximity Detection

Discussion

Heart Rate

While there are various kinds of hemoglobin compounds present in blood, for SpO2 calculations it is assumed that oxygenated hemoglobin and deoxygenated hemoglobin are the only significant factors. In a reflective pulse-oximetry set up, LEDs illuminate skin tissue and the reflected signal is detected by the photodiode. This reflected signal contains the light that was optically modulated by the volumetric changes of the arteries and capillaries. This photoplethysmography (PPG) signal is extremely important in determining heart rate and SpO2 levels. PPG signals have a DC component and an AC component combined with it, as can be seen below in **Figure 1**.

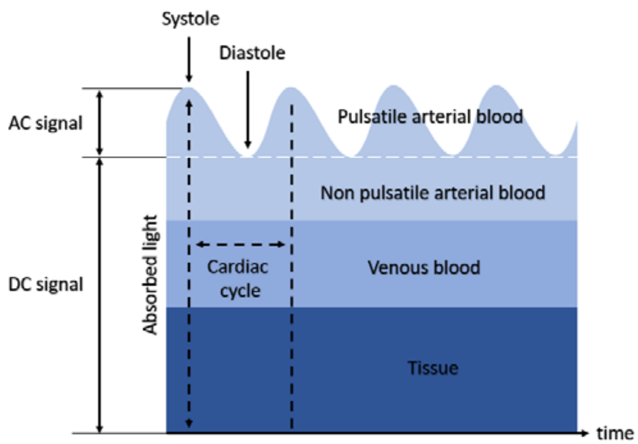


Figure 1. DC and AC components of a PPG signal.

The DC component is attributed to the light absorption of nonpulsatile tissue: venous capillary and arterial blood.[1] The AC component, on the other hand, is due to the pulsatile nature of arterial blood. Since arteries have a direct connection to the heart, the arterial blood pulsates as the heart pulsates. Instantaneous heart rate can be calculated by measuring the time between consecutive systolic peaks.

It is important to note here that heart rate can be measured by using just one LED, red for instance, as the AC component is the only signal needed.

SpO2

MAX3010x SpO2 measurements employ two different wavelength LEDs to identify the ratio of oxygenated hemoglobin to the deoxygenated hemoglobin. Red and IR LEDs are used to determine separate PPG signals. As the DC components and AC components of the two LEDS have different amplitudes, they must be normalized to make useful comparisons. For this comparison, a ratio 'R' is determined, which is directly proportional to SpO2. Before the equations for R and SpO2 are introduced, it should be noted that SpO2 approximates arterial oxygen saturation (SaO2). SpO2 measurements are commonly found in fitness/medical applications due to its good approximation of SaO2.[2] The following equation for R is known as "ratio of ratios:"

$$R = \frac{\frac{AC_{red}}{DC_{red}}}{\frac{AC_{infrared}}{DC_{infrared}}}$$

Once R is determined, a curvilinear approximation or a lookup table can be used to determine the SpO2 estimate. This data is typically collected by empirical methods where numerous subjects are used. Age, skin tone, overall health, and medical conditions can affect the accuracy of the SpO2 measurement. Below is a linear approximation example derived from a best-fit straight-line approximation of SpO2 vs. R data (S. Prahl [3]) between the R-range of 0.4 to 3.4:

$$SpO_2 = 104 - 17R$$

Note: *The MAX30101 EV kit GUI can log data in CSV format, but post-processing is required when MAX30101 is used in an application to determine HR and/or SpO2. This user guide provides a brief mention of the challenges associated with post processing and how a user can make sense of the graphical data.*

Default EV Kit

When the user initiates the MAX30101 EV kit GUI, **Figure 2** shows what the GUI should look like. Two very basic example algorithms are provided with the GUI. These simple algorithms provide numerical estimates of HR and SpO2.

The GUI allows the user to log raw data from the ADC. While the Maxim Integrated user interface can be used to visually determine functionality of the MAX3010x device, post processing is required to determine the numerical values of HR and SpO2.

The main GUI window, on the left, has graphical plots for optical measurements and accelerometer measurements. The optical measurements show data corresponding to the LED mode selected. For example, if LED slot 1 has "3 LED3(Green)" selected and LED slots 2 to 4 have "0 Disabled" selected, then optical measurements only show green measurements when the GUI is operational. The accelerometer measurement plot shows three axes of linear acceleration.

On the left, Mode Configuration, Settings, LED currents, Proximity, and LED Mode Timing slot settings are provided for the user to configure the MAX30101 device.

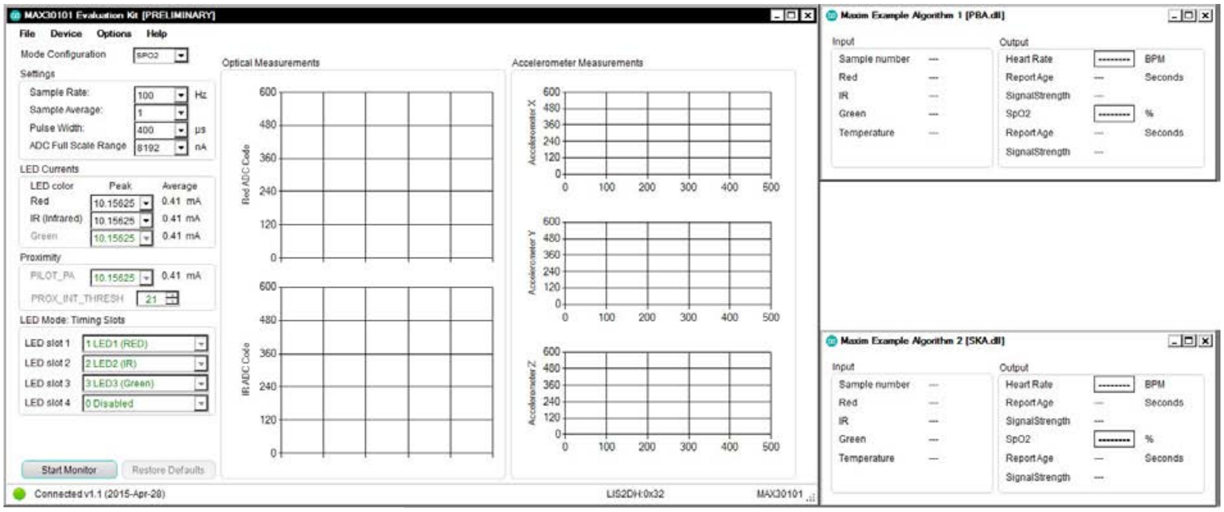


Figure 2. Default EV Kit GUI screen.

Flowchart for General EV Kit Operation

The flowchart below (**Figure 3**) shows a general setup for getting started with MAX30101. The user should make sure that the sensor board and microcontroller are connected properly.

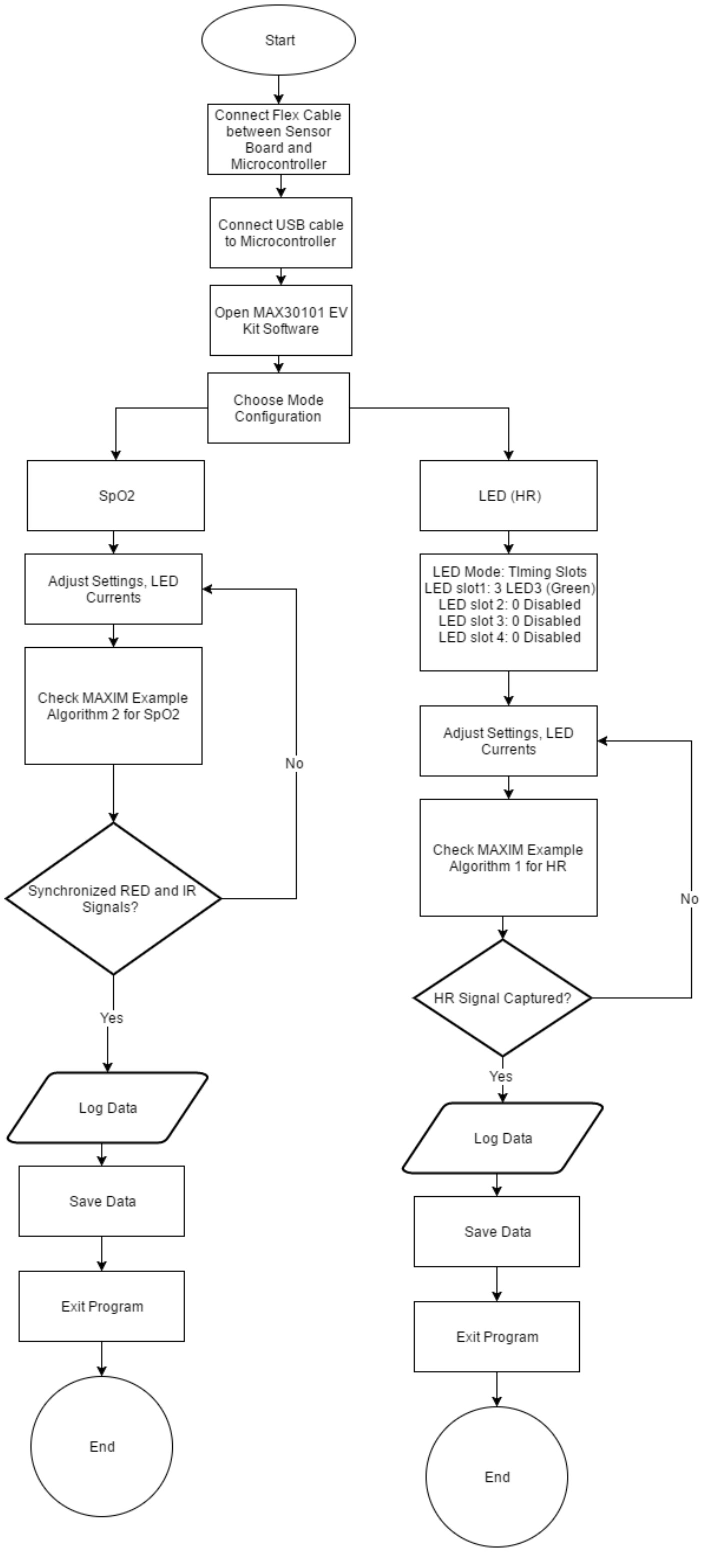
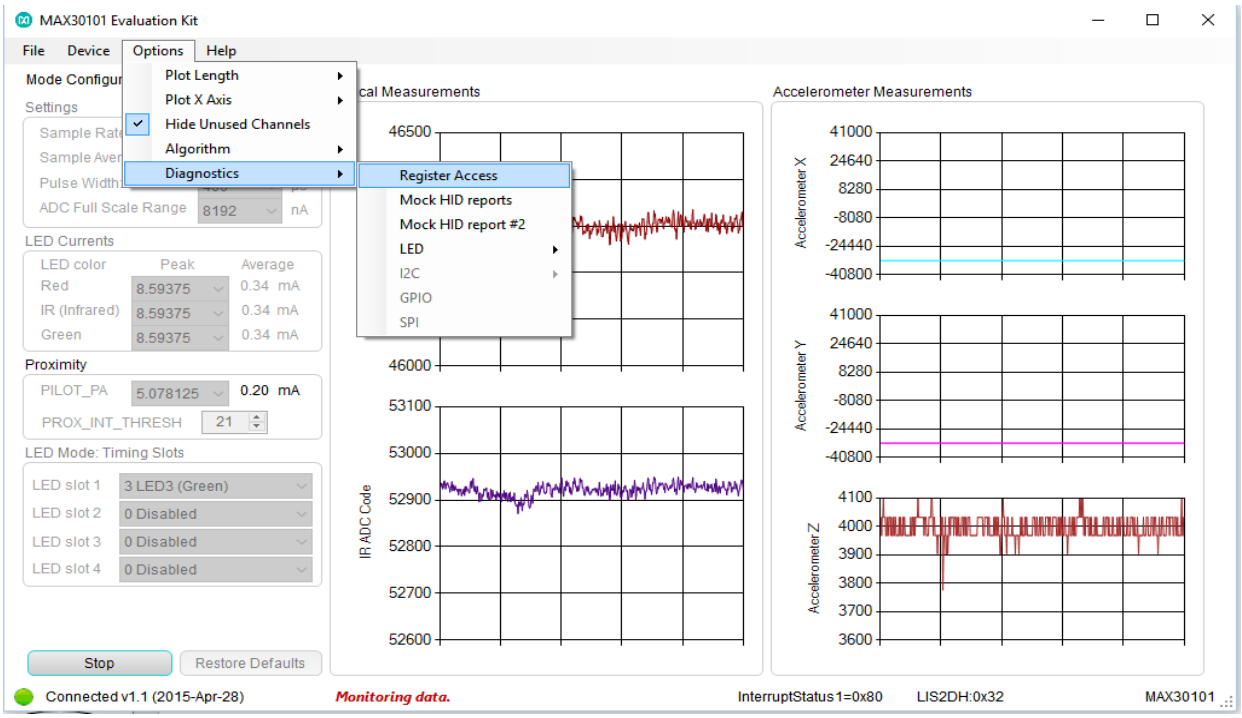
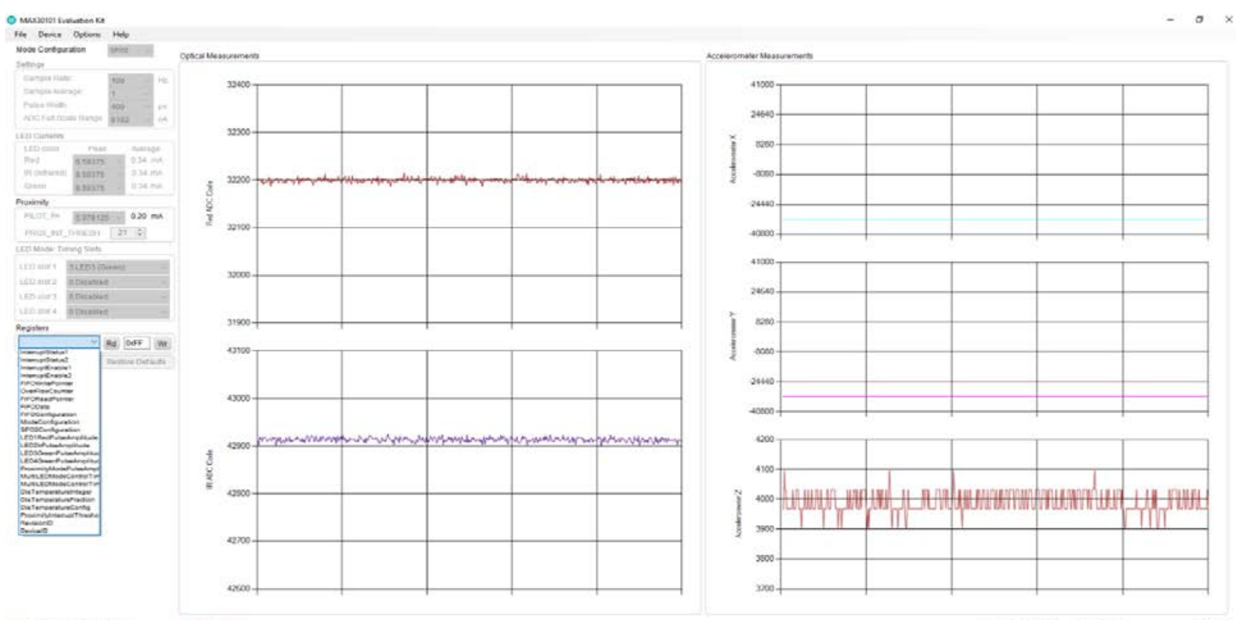


Figure 3. General setup for using MAX30101.

Implementing Specific Configurations

Changing the GUI settings is intuitive and allows the user to experiment with them before use. However, it is important to note that if the user wants to read or write new register values, the MAX30101 GUI needs to be operational. This can be extremely useful as this provides direct access to the registers of the operational MAX30101. The user should study the MAX30101 data sheet in depth and use this user guide to optimize MAX30101 use. **Figure 4** shows how the registers can be accessed during operation followed by a recommended way of using the MAX30101 EV kit for heart rate (HR) and SpO2.





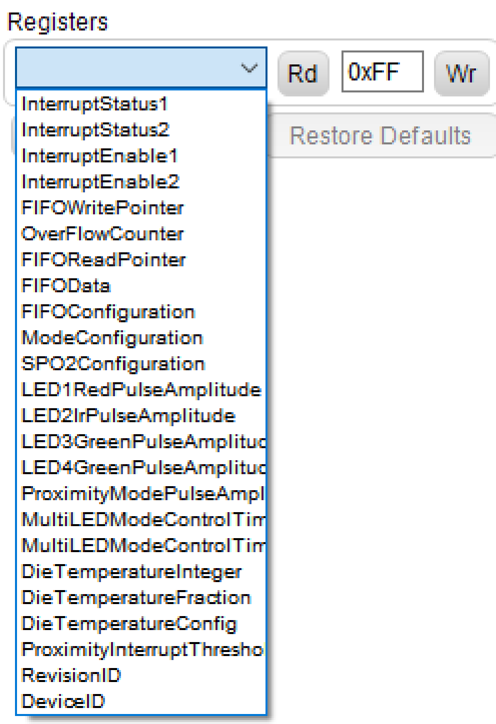


Figure 4. Accessing registers while the EV kit GUI is in operation.

Expected Heart-Rate (HR) Signals

Before discussing the recommended register configurations, **Figure 5**, **Figure 6**, **Figure 7**, and **Figure 8** show what the expected heart-rate signal should look like and what happens when LED-current settings are changed. Ideally, applications requiring a good HR signal require a higher LED current. But if low power consumption is desired, then the user should consider lowering the LED current. The issue with this is that the SNR lowers when reducing pulse width and sample rate. To resolve this issue, the user should try different LED currents to determine an optimal setting. Figure 5 through Figure 8 show HR signals when captured at average currents of 0.04mA (peak = 1), 0.13mA (peak = 3.125), 0.20mA (peak = 5.078125), and 0.41mA (peak = 10.15625). The peak value refers to the peak current level for the LEDs in mA.

Note: *Green LEDs are typically used for wrist HR monitoring instead of Red or IR LEDs, sensing blood pulsations where perfusion is reduced. The Green PPG is influenced by DC to a smaller degree.*[4]

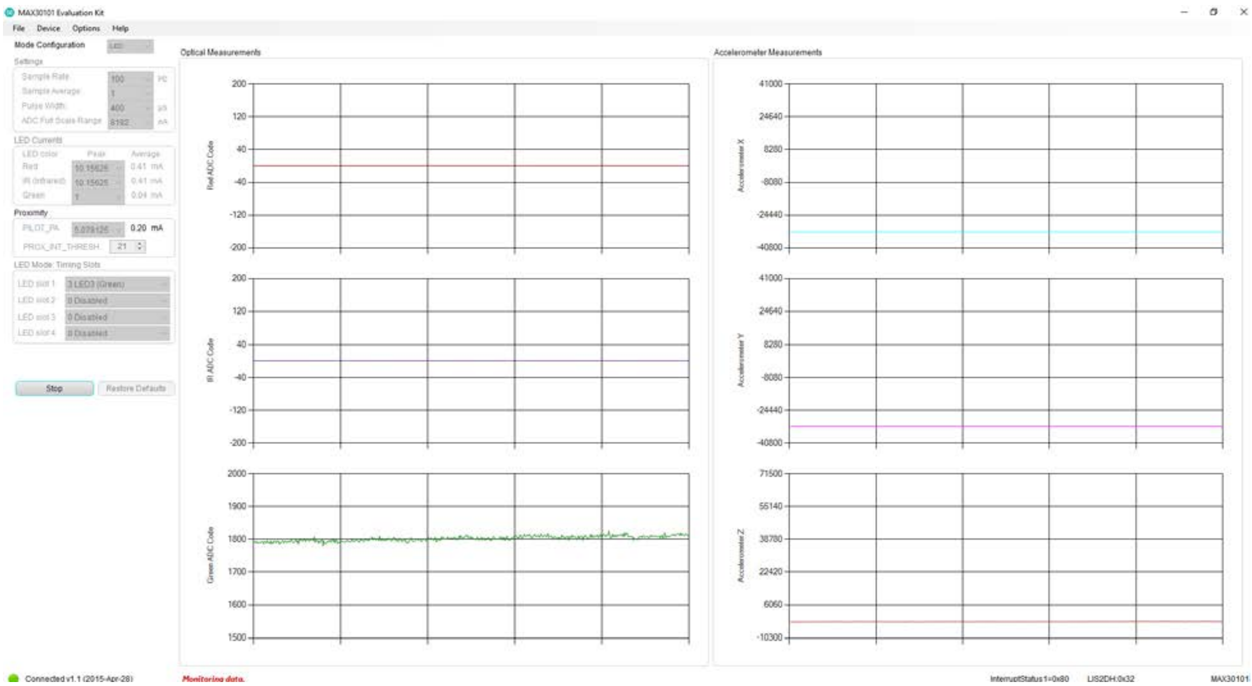


Figure 5. Data recorded by the GUI when a Green LED is used at 0.04mA.

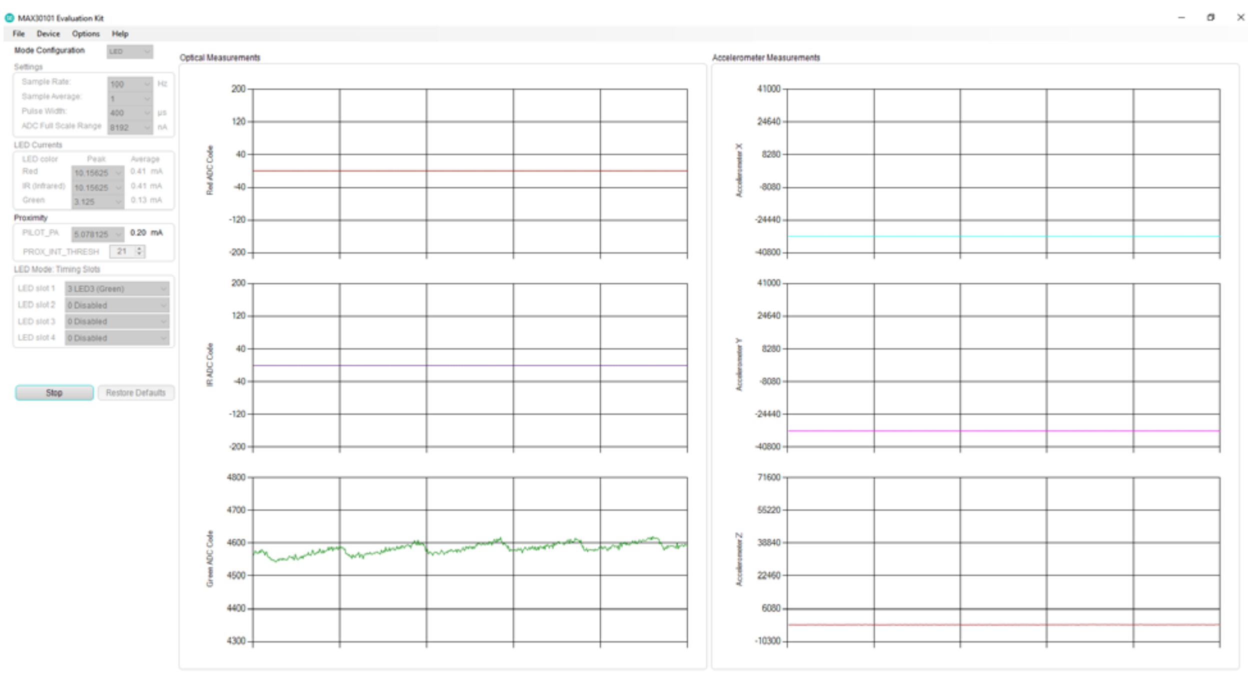


Figure 6. Data recorded by the GUI when a Green LED is used at 0.13mA.

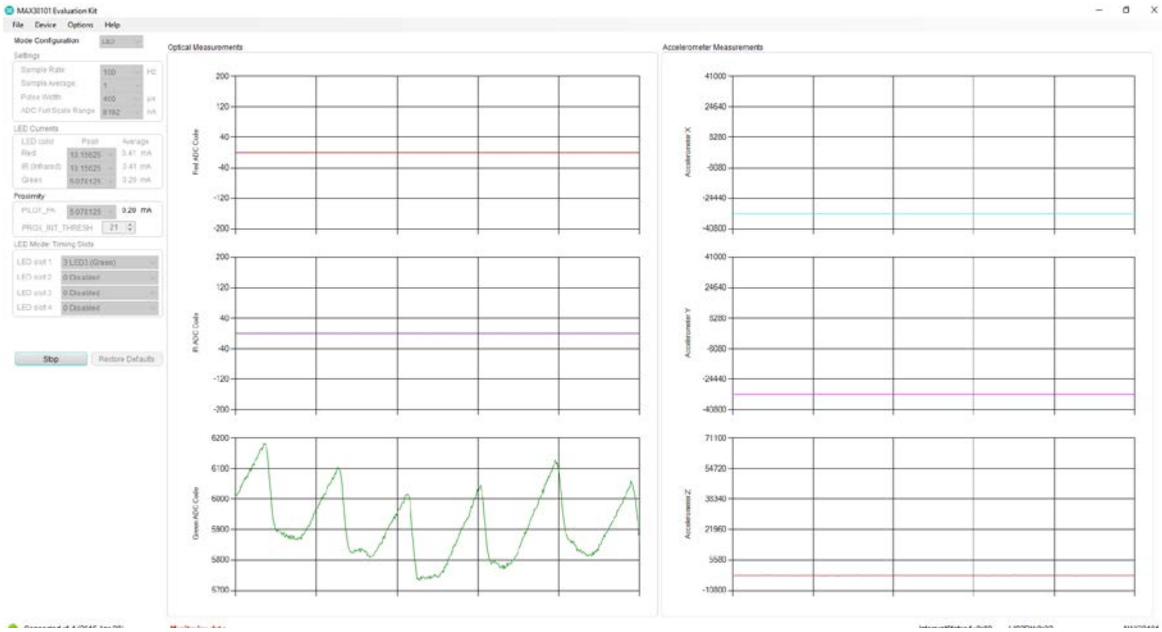


Figure 7. Data recorded by the GUI when a Green LED is used at 0.20mA.

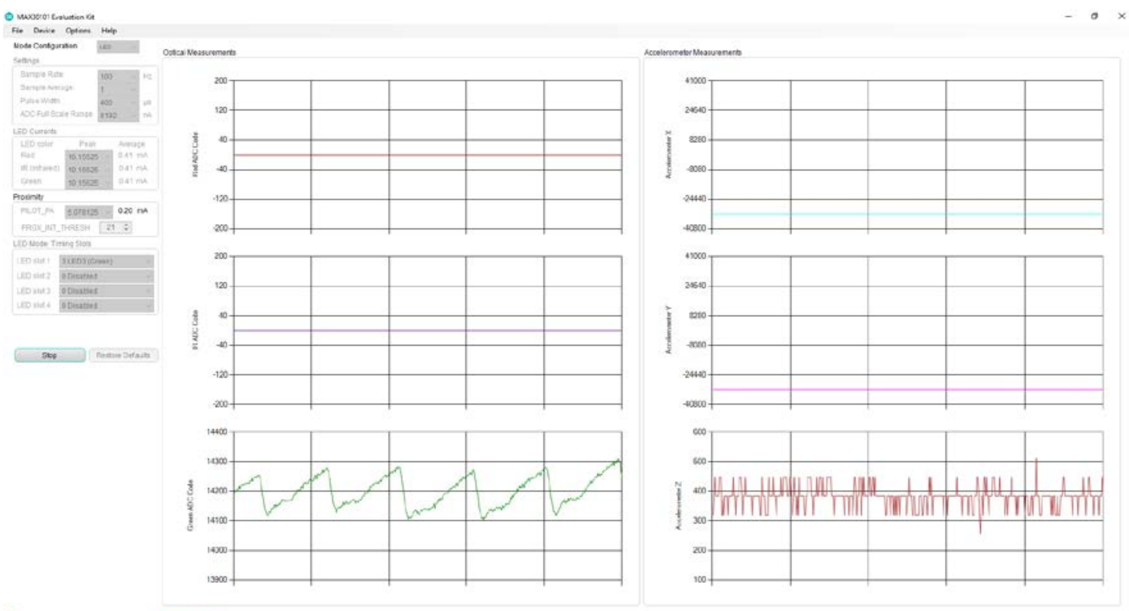


Figure 8. Data recorded by the GUI when a Green LED is used at 0.41mA.

The MAX3010x digitizes the photo-diode signal using an internal ADC. As can be seen in the figures above, Red and IR-ADC code “flatlined” at 0 as these LEDs were disabled. The motion was kept to a minimum, as can be seen by the flat line on the accelerometer axes. While keeping all settings the same in each configuration (Figure 5 to Figure 8), only the LED currents were changed. As the GUI was designed to auto-scale the ADC output signal, the y-axis range changes as displayed in the above figures. The ADC count (on the y axis of Green ADC code) shows the peak-to-peak counts increased as the current was increased. Higher LED current results in a brighter LED. These figures illustrate that no HR signal was captured at 0.04mA (peak = 1). The current had to be about 0.20mA (peak = 5.078125) for MAX30101 to capture the signal.

Note: *The user can change settings to measure an improved HR signal if necessary.*

Expected SpO2 Signals

Using the same procedure mentioned above for the ***Expected Heart-Rate Signals***, LED currents can be minimized, but need to be kept high enough so that a good SpO2 signal is captured. Since Red and IR LEDs are being used, the user can configure each LED amplitude (i.e., current) to find the optimal configuration for their application. **Figure 9** shows a possible configuration when SpO2 mode is being used. A 0.41mA (peak = 10.15625) average signal setting is used for both LEDs. The user should note that the two signals (Red and IR) are in sync while their amplitudes have different strengths. Post processing requires the user to first normalize the data, as mentioned in the ***In-Depth Discussion***, and then use the normalized Red and IR to find a ratio corresponding to the SpO2.

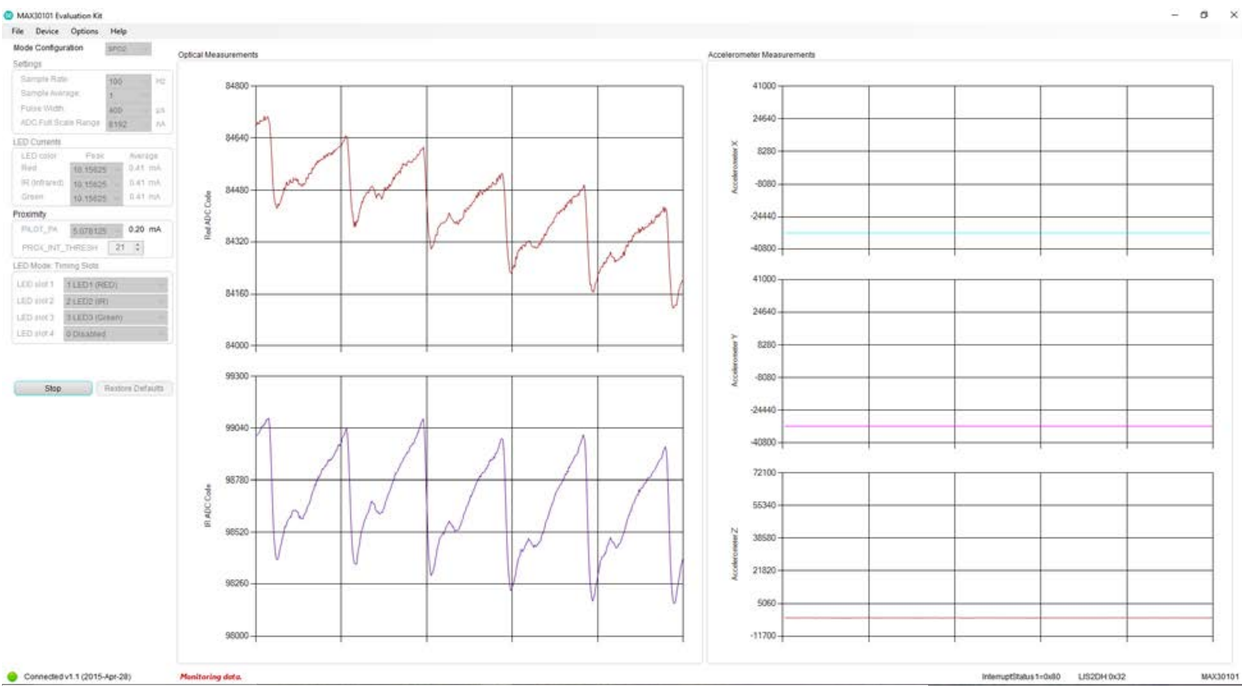


Figure 9. Data recorded by the GUI when Red and IR LEDs are used at 0.41mA.

General Recommendations

Before proceeding, it should be noted that a pulse width tells how long in time a signal is active for. In terms of power consumption, the longer a signal is active, the more energy it consumes. The drive frequency for the LEDs is selected by the sample rate. Correspondingly, a higher sample rate results in a higher drive frequency, thereby consuming more energy.

The ideal option for a wearable application is to choose lower pulse width combined with a lower sample rate to minimize energy consumption. However, this does not work since pulse width has an inverse relationship with the sample rate. This follows from the reasoning that a higher pulse width corresponds to a lower drive frequency and vice versa.

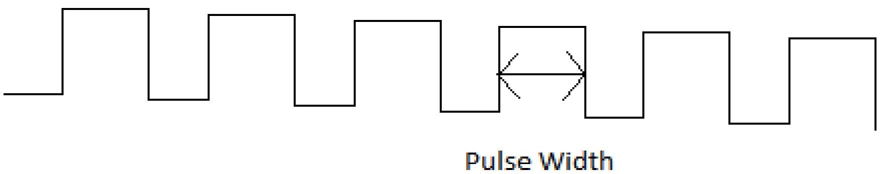


Figure 10. Pulse width example.

Figure 11 and **Figure 12** show what the allowed settings are for HR (single LED mode), and SpO2 (dual LED mode). The shaded boxes correspond to settings that are not allowed. The user should adjust the pulse width and samples per second to determine the best settings for their application.

SAMPLES PER SECOND	PULSE WIDTH (µs)			
	69	118	215	411
50	O	O	O	O
100	O	O	O	O
200	O	O	O	O
400	O	O	O	O
800	O	O	O	O
1000	O	O	O	O
1600	O	O	O	
3200	O			
Resolution (bits)	15	16	17	18

Figure 11. Allowed settings for heart rate configuration.

SAMPLES PER SECOND	PULSE WIDTH (µs)			
	69	118	215	411
50	O	O	O	O
100	O	O	O	O
200	O	O	O	O
400	O	O	O	O
800	O	O	O	
1000	O	O		
1600	O			
3200				
Resolution (bits)	15	16	17	18

Figure 12. Allowed settings for SpO2 configuration.

SPO2 Register-Level Operation

The default mode is for pulse-oximetry (SpO2) measurements using Red and IR LEDs only. These selections are bolded on the GUI screen.

Register Map and General Guidelines

Figure 13 is also provided in the MAX30101 data sheet. The different registers are grouped together for convenience.

The Mode Configuration (0x09) register is used for shutdown control (SHDN), reset control (RESET), HR mode, SpO2 mode, and multi-LED mode. Shutdown control allows the user to put MAX30101 in power-saving mode. When the reset bit is set to one, all configuration, threshold, and data registers are reset to their power-on state through a power-on reset. Mode [3:0] allows the user to choose the modes such as HR, SpO2, or Multi-LED.

Mode Configuration (0x09)

REGISTER	B7	B6	B5	B4	B3	B2	B1	B0	REG ADDR	POR STATE	R/W
Mode Configuration	SHDN	RESET				MODE[3:0]			0x09	0x00	R/W

MODE[2:0]	MODE	ACTIVE LED CHANNELS
000	Do not use	
001	Do not use	
010	Heart Rate mode	Red only
011	SpO2 mode	Red and IR
100–110	Do not use	
111	Multi-LED mode	Green, Red, and/or IR

SpO_2 Configuration (0x0A)

REGISTER	B7	B6	B5	B4	B3	B2	B1	B0	REG ADDR	POR STATE	R/W
SpO_2 Configuration		SPO2_ADC_RGE<1:0>		SPO2_SR[2:0]			LED_PW[2:0]		0x0A	0x00	R/W

SPO2_ADC_RGE[1:0]	LSB SIZE (pA)	FULL SCALE (nA)
00	7.81	2048
01	15.63	4096
02	31.25	8192
03	62.5	16384

SPO2_SR[2:0]	SAMPLES PER SECOND
000	50
001	100
010	200
011	400
100	800
101	1000
110	1600
111	3200

Figure 13. Mode register, available modes, and SpO2 registers.

SpO2_ADC_RGE corresponds to SpO2 ADC Range Control where bits can set the SPO2 sensor ADC's full-scale range from 2048nA to 16384nA. The default full-scale range is 8192nA.

SPO2_SR corresponds to SpO2 Sample Rate Control where bits can set the effective sampling rate with one sample consisting of one IR pulse/conversion and one Red pulse/conversion. The default sampling rate is 100 samples per second (Hz).

LED_PW corresponds to LED pulse width. IR, Red, and Green have the same pulse width, but this pulse width can be varied from 69µs to 411µs. ADC resolution is proportional to the pulse width. As pulse width is increased, ADC resolution is also increased. This is shown in **Figure 14**.

LED_PW[1:0]	PULSE WIDTH (µs)	ADC RESOLUTION (bits)
00	69 (68.95)	15
01	118 (117.78)	16
10	215 (215.44)	17
11	411 (410.75)	18

Figure 14. LED pulse-width control.

In SpO2 mode, each sample consists of 6 bytes of data and each byte requires an I^2C read to read a sample. Refer to ***FIFO*** section for a detailed discussion on FIFO operation.

LED-Pulse Amplitude and Current Control

As SpO2 mode and Heart rate mode both employ LEDs, the following section applies to both modes. It provides register level insight into LED pulse control.

Figure 15 is provided in the MAX30101 data sheet. The different registers are grouped together for convenience.

LED-pulse amplitude registers (0x0C to 0x10) allow the user to set the typical LED current in milliamps (mA). This can be adjusted from 0.0mA to 50mA peak amplitude.

Multi-LED mode allows the user to determine which LEDs are active. This mode is divided into a maximum of four FIFO time slots which can be modified using SLOT bits (i.e., SLOT 2 [2:0], SLOT 1 [2:0]). The slots also determine the size of the sample. For example, if one slot is being used, then one sample is 3 bytes long. If two slots are being used, then the sample size becomes 6 bytes long, and so on. The figure below also shows which bit configuration should be used for the LED being used. For instance, to turn on Green LED, the SLOT bit setting should be 011.

Multi-LED mode can also be used in proximity mode. Here the PILOT_PA bits set LED power and SLOT settings 101, 110, and 111 allow the user to choose active LEDs during proximity mode.

LED Pulse Amplitude (0x0C–0x10)

REGISTER	B7	B6	B5	B4	B3	B2	B1	B0	REG ADDR	POR STATE	R/W
LED Pulse Amplitude	LED1_PA[7:0]								0x0C	0x00	R/W
	LED2_PA[7:0]								0x0D	0x00	R/W
LED Pulse Amplitude	LED3_PA[7:0]								0x0E	0x00	R/W
RESERVED									0x0F	0x00	R/W
Proximity Mode LED Pulse Amplitude	PILOT_PA[7:0]								0x10	0x00	R/W

LEDx_PA [7:0], RED_PA[7:0], IR_PA[7:0], or G_PA[7:0]	TYPICAL LED CURRENT (mA)*
0x00h	0.0
0x01h	0.2
0x02h	0.4
...	...
0x0Fh	3.1
...	...
0x1Fh	6.4
...	...
0x3Fh	12.5
...	...
0x7Fh	25.4
...	...
0xFFh	50.0

Multi-LED Mode Control Registers (0x11–0x12)

REGISTER	B7	B6	B5	B4	B3	B2	B1	B0	REG ADDR	POR STATE	R/W
Multi-LED Mode Control Registers		SLOT2[2:0]				SLOT1[2:0]			0x11	0x00	R/W
		SLOT4[2:0]				SLOT3[2:0]			0x12	0x00	R/W

SLOTx[2:0] Setting	WHICH LED IS ACTIVE	LED PULSE AMPLITUDE SETTING
000	None (time slot is disabled)	N/A (Off)
001	LED1 (RED)	LED1_PA[7:0]
010	LED2 (IR)	LED2_PA[7:0]
011	LED3 (GREEN)	LED3_PA[7:0]
100	None	N/A (Off)
101	LED1 (Red)	PILOT_PA[7:0]
110	LED2 (IR)	PILOT_PA[7:0]
111	LED3 (GREEN)	PILOT_PA[7:0]

Figure 15. LED-pulse amplitude register and multi-LED mode control registers.

SpO2 Recommended Configuration

A recommended methodology is presented here for determining an appropriate configuration and operating profile for the use of Maxim Integrated's MAX30101 SpO2 sensor device. While differing applications (e.g., fingertip, forehead, ear, etc.) influence corresponding settings, the basic procedure is similar for most use cases.

Disclaimer: This document addresses only the signals that are derived from the MAX30101 device. That is, only the ADC outputs from the Red LED and Infrared LED channels are considered. Thus, settings are recommended that maximize signal-to-noise ratios, while preserving dynamic range and minimizing operating power. The ultimate test of performance vs. settings should be evaluated using an algorithm designed to process pulse oximeter digital data.

1. Set the SPO2_ADC_RGE[1:0] to 00 to place the ADC in its highest gain setting (full scale = 2.048µA). Leave the Pulse Amplitude setting at the default value for now (approximately 10mA). Both the Red and IR channels should be set to the same value.

   If the channel is saturated, adjust the gain setting to the next lower setting (SPO2_ADC_RGE[1:0] = 01). Adjust the gain setting (SPO2_ADC_RGE[1:0]) until the signal is somewhere between ¼ full scale (FS) and ¾ FS. The user should be looking at the average level of the DC + pulsatile signal.

   Note: *A pulsatile signal is typically less than 1% of the FS range.*

   Note: *A user can use a setting level where operation is outside the ¼ to ¾ FS range. The above procedure is meant as a general guide to make a user aware of the dynamic range available. The use case needs to be fully characterized with multiple test subjects and appropriate ambient conditions. The gain setting (along with the pulse amplitude, width, sample rate, etc.) must be selected so that the sensor has appropriate dynamic range for the use case.*

2. Next set the SpO2 LED current settings (LED1_PA [7:0] and LED2_PA[7:0]). The default value is approximately 10mA. This value can typically be reduced to save power. The amplitude and pulse-width settings can be adjusted to lower power. However, this sets signal-strength level. The user must make the decision of acceptable signal strength vs. power level.

   If the signal strength is low enough, the gain setting can be lowered, adjusting the dynamic range. If low power operation is desired, an iterative process between adjusting the dynamic range and the LED amplitude occurs until desired settings are found.

   Figure 16 shows the MAX30101 SpO2 signals. Distinct and synchronized pulsatile signals must exist on both the Red and IR channels for further SpO2 processing. This graph is in our EV kit data sheet.

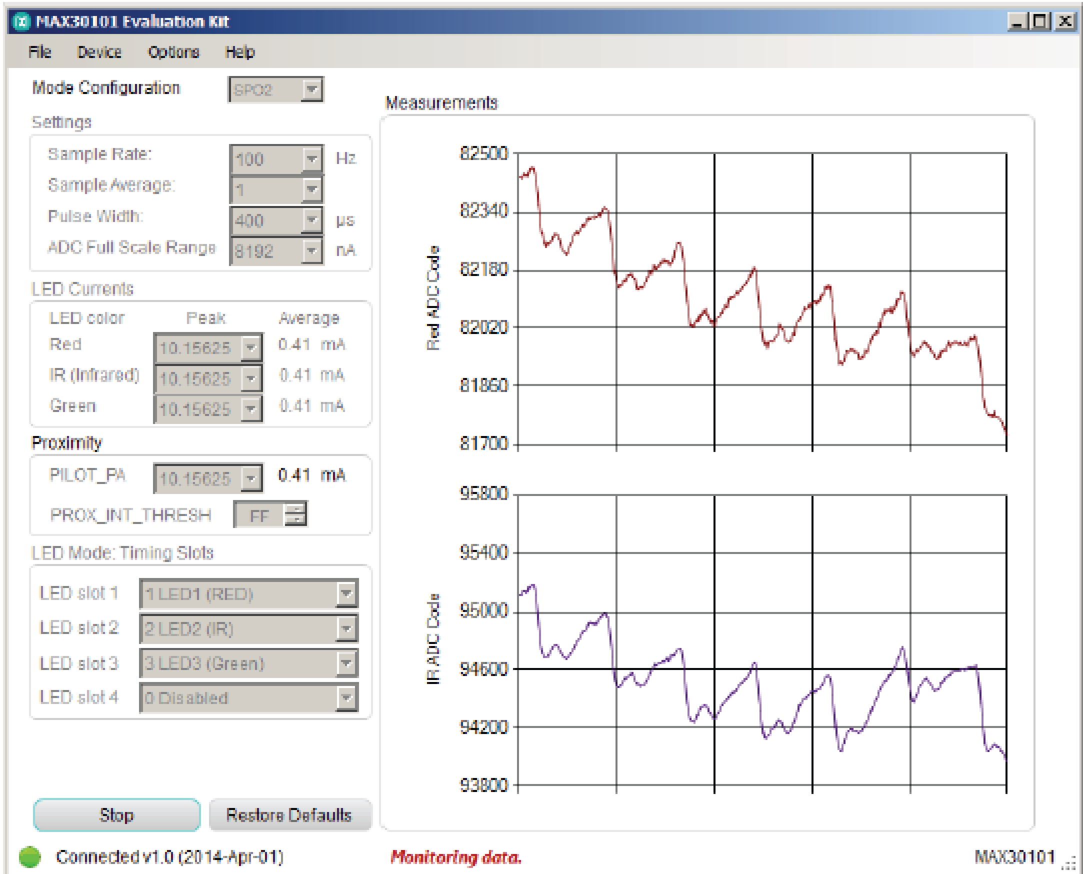


Figure 16. Red and IR showing SpO2 signals in sync.

Using the EV kit, a user can lower the current amplitudes until the synchronized signals disappear (visually). Putting some margin on this setting (e.g., double the current setting) can give a user a starting point for use case evaluations.

Note: *This setting level should* ***<u>not</u>*** *be used for determining the final setting configuration. It is highly recommended that a user collect data and set the performance level with the use of an SpO2 algorithm. In this manner, a user can optimize the power setting vs. performance metric of choice (e.g., SNR, perfusion index, PPG var, etc.).*

Heart Rate Monitoring for Wrist Application:

As mentioned previously, Red and IR LEDs can be used to measure heart rate. However, they are not as effective for wrist measurements. The wrist is generally not a convenient place for capturing HR and/or SpO2 signals. A higher energy signal (Green LED) is used for wrist applications because of diminished blood perfusion in the wrist. To configure the EV kit for wrist HR measurements, several settings must be changed. The first is to change the Mode Configuration selection to “LED.” **Figure 17** shows the initial SpO2 screen and the screen when the LED is selected.

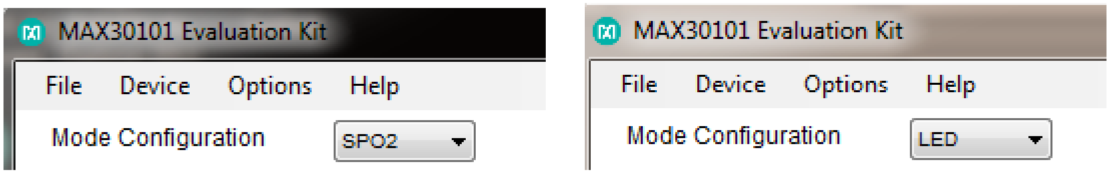


Figure 17a and 17b. SpO2 mode and LED mode (for wrist HR applications).

When the “LED” Mode Configuration is selected, the LED Mode: Timing Slots window is highlighted. This mode implements all three LEDs in operation. **Figure 18** shows this default configuration.

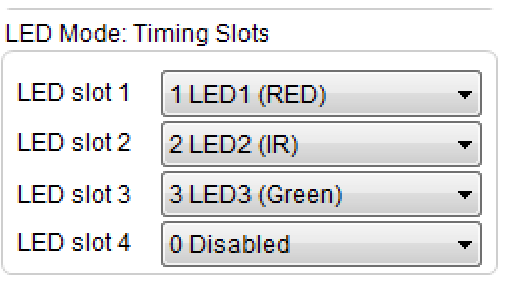


Figure 18. LED-mode timing slots.

Two Maxim Integrated example algorithms are included in the EV kit GUI. These basic algorithms are supplied for demonstration purposes only and Maxim Integrated does not guarantee their accuracy. Further, these algorithms do not provide motion compensation. To use the algorithms for wrist HR measurements, the following modifications are required:

1. Change LED slot 1 to “3LED3 (Green).”
2. Disable LED slot 2.
3. Disable LED slot 3 (automatically disables when slot 2 is disabled).

After these changes are made, the GUI screen looks like **Figure 19**.

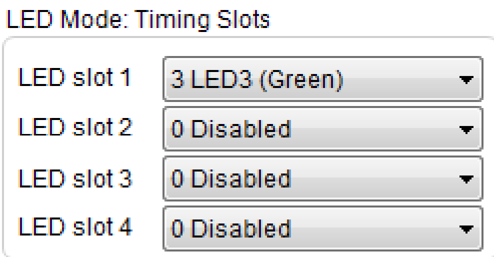


Figure 19. LED mode timing slots for wrist HR measurements.

Wrist HR measurements generally require higher signal levels. This can be accomplished by adjusting the ADC FS range to 4096nA and/or adjusting the LED currents (**Figure 20**).

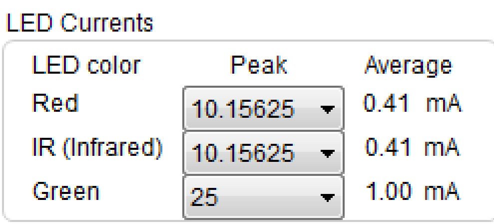


Figure 20. Changing the Green LED current.

While the GUI is not operating, all three plots (Red, IR, and Green) are visible on the GUI screen. As soon as Start Monitor is engaged, only the Green LED measurement is active (**Figure 21**).

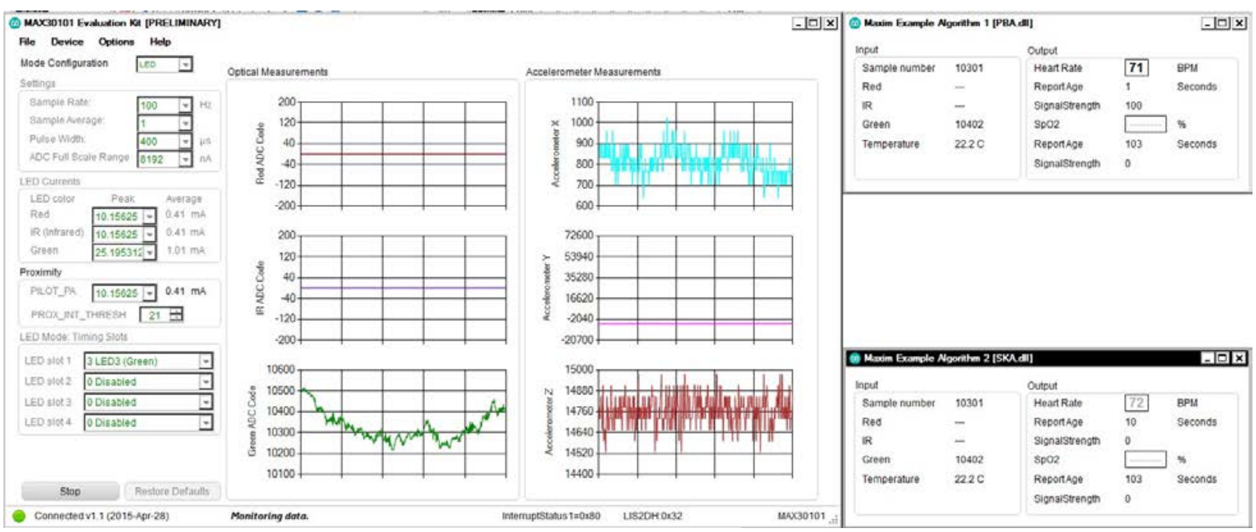


Figure 21. Wrist HR measurement using the MAX30101 EV kit.

The configuration of the LED3 (Green) through LED slot 1 allows the computation of the heart rate using the simple algorithms that are supplied with the EV kit GUI. The next section shows how a user can increase the Green LED signal.

Increasing the Green LED Signal

Within the Integrated Circuit, Channel 3 (i.e., Green LED) is tied internally to Channel 4. Thus, a user can configure the drive signal to a higher level. While the GUI is running, select "Options" from the pull-down tab. Next, select "Register Access" (**Figure 22**).

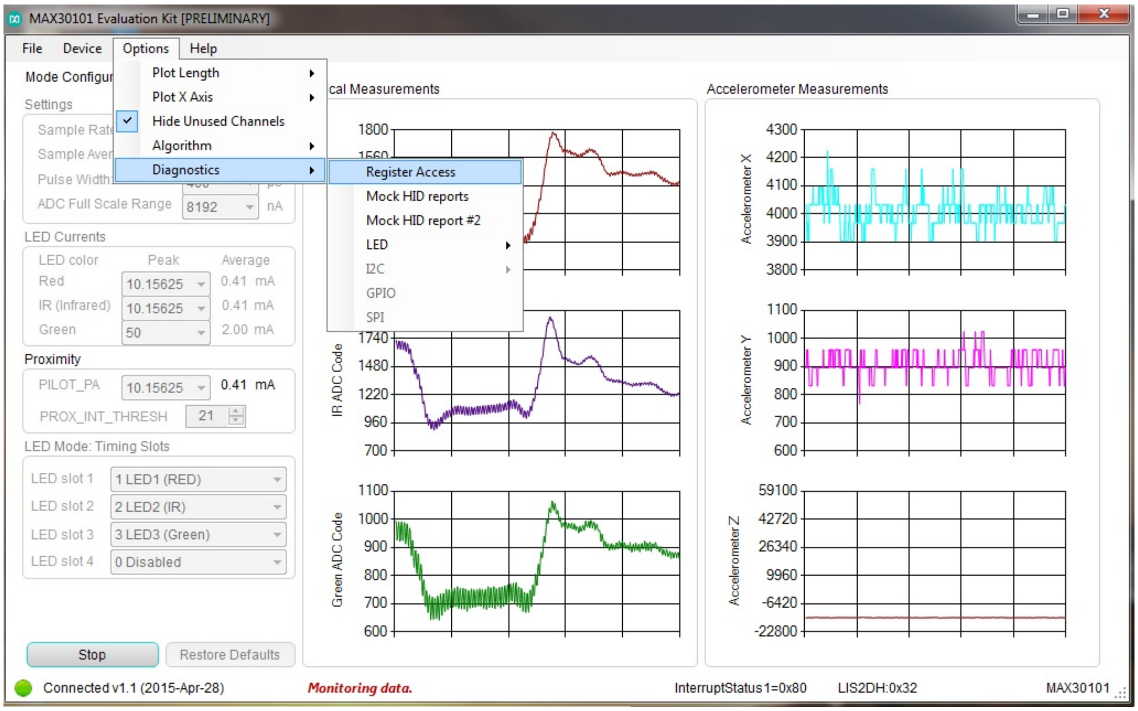


Figure 22. Register access while the GUI is operating.

Four new windows appear showing a "Registers" selection, value, Read Command ("Rd") button, and a Write Command ("Wr") button (**Figure 23**).

The changing of register values can only occur while the GUI is operational. As soon as the GUI is stopped, the S/W returns to its default setup configuration.

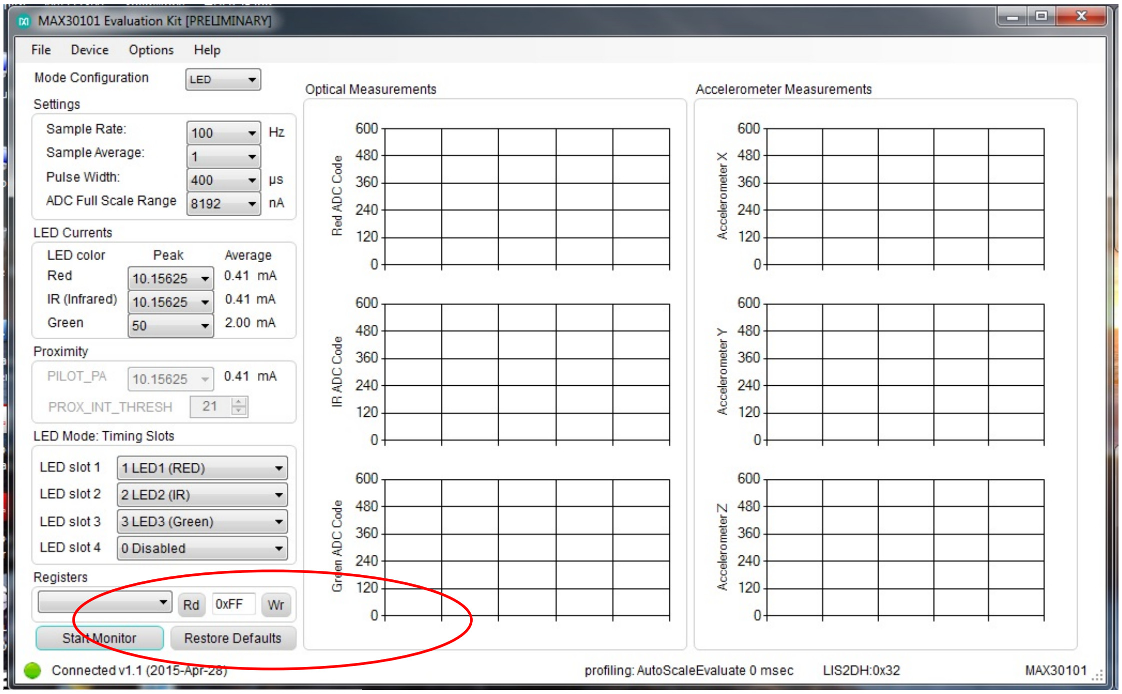


Figure 23. GUI register access.

Next, select the "LED4GreenPulseAmp" register, fill in the value of "0xFF," and hit "Wr." The Green LED is configured to its maximum level of approximately 80mA. Any value between "0x00" and "0xFF" can be selected (**Figure 24**).

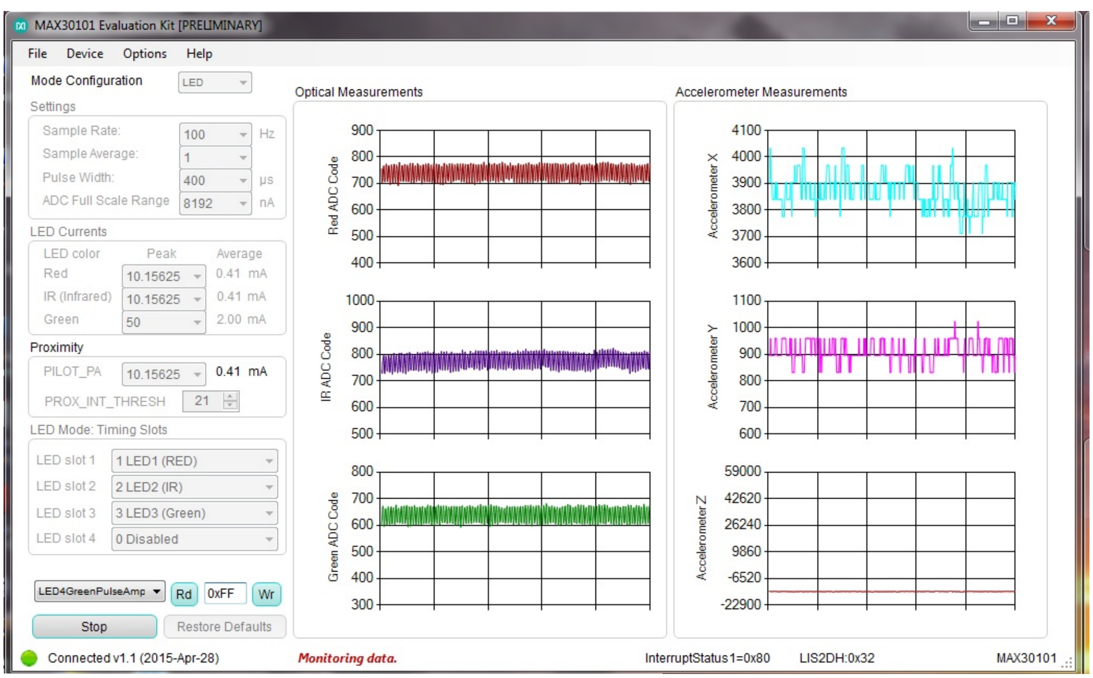


Figure 24. Input values in LED4GreenPulseAmp register.

Register Map

Interrupts

Figure 25 is provided in the MAX30101 data sheet.

Interrupt Status (0x00–0x01)

REGISTER	B7	B6	B5	B4	B3	B2	B1	B0	REG ADDR	POR STATE	R/W
Interrupt Status 1	A_FULL	PPG_RDY	ALC_OVF	PROX_INT				PWR_RDY	0x00	0X00	R
Interrupt Status 2							DIE_TEMP_RDY		0x01	0x00	R

Interrupt Enable (0x02-0x03)

REGISTER	B7	B6	B5	B4	B3	B2	B1	B0	REG ADDR	POR STATE	R/W
Interrupt Enable 1	A_FULL_EN	PPG_RDY_EN	ALC_OVF_EN	PROX_INT_EN					0x02	0X00	R/W
Interrupt Enable 2							DIE_TEMP_RDY_EN		0x03	0x00	R/W

Figure 25. Interrupt status and interrupt enable registers.

The interrupts triggered by Interrupt status 1 and Interrupt status 2 are as follows: FIFO almost full flag (A_FULL), new FIFO data ready (PPG_RDY), ambient light cancellation overflow (ALC_OVF), proximity threshold triggered (PROX_INT), power ready flag (PWR_RDY).

As ambient light can easily introduce error into the HR and SpO2 measurement, MAX30101 incorporates an Ambient Light Correction (ALC) feature that removes ambient light. Generally, the goal is to minimize the ambient light to isolate the desired signal. As such, ambient light should be kept in mind when designing enclosures and spacing of the photodiodes from the skin. In terms of the register map, it is important to note the ALC_OVF interrupt indicates that ambient light cancellation function has reached its maximum light and is affecting the output of ADC.

Data Streaming and FIFO Operation

Figures 26 and **27** are provided in the MAX30101 data sheet.

FIFO (0x04–0x07)

REGISTER	B7	B6	B5	B4	B3	B2	B1	B0	REG ADDR	POR STATE	R/W
FIFO Write Pointer				FIFO_WR_PTR[4:0]					0x04	0x00	R/W
Over Flow Counter				OVF_COUNTER[4:0]					0x05	0x00	R/W
FIFO Read Pointer				FIFO_RD_PTR[4:0]					0x06	0x00	R/W
FIFO Data Register	FIFO_DATA[7:0]								0x07	0x00	R/W

ADC Resolution	FIFO_DATA[17]	FIFO_DATA[16]	⋮	FIFO_DATA[12]	FIFO_DATA[11]	FIFO_DATA[10]	FIFO_DATA[9]	FIFO_DATA[8]	FIFO_DATA[7]	FIFO_DATA[6]	FIFO_DATA[5]	FIFO_DATA[4]	FIFO_DATA[3]	FIFO_DATA[2]	FIFO_DATA[1]	FIFO_DATA[0]
18-bit																
17-bit																
16-bit																
15-bit																

BYTE 1							FIFO_ DATA[17]	FIFO_ DATA[16]
BYTE 2	FIFO_ DATA[15]	FIFO_ DATA[14]	FIFO_ DATA[13]	FIFO_ DATA[12]	FIFO_ DATA[11]	FIFO_ DATA[10]	FIFO_ DATA[9]	FIFO_ DATA[8]
BYTE 3	FIFO_ DATA[7]	FIFO_ DATA[6]	FIFO_ DATA[5]	FIFO_ DATA[4]	FIFO_ DATA[3]	FIFO_ DATA[2]	FIFO_ DATA[1]	FIFO_ DATA[0]

FIFO Configuration (0x08)

REGISTER	B7	B6	B5	B4	B3	B2	B1	B0	REG ADDR	POR STATE	R/W
FIFO Configuration	SMP_AVE[2:0]			FIFO_ROL LOVER_EN	FIFO_A_FULL[3:0]				0x08	0x00	R/W

SMP_AVE[2:0]	NO. OF SAMPLES AVERAGED PER FIFO SAMPLE
000	1 (no averaging)
001	2
010	4
011	8
100	16
101	32
110	32
111	32

Figure 26. FIFO registers.

FIFO_A_FULL[3:0]	ALMOST FULL INTERRUPT TRIGGER (NO. OF SAMPLES IN THE FIFO)
0x0h	0
0x1h	1
0x2h	2
0x3h	3
...	...
0xFh	15

Figure 27. FIFO_A_FULL registers and how they correspond to number of samples in FIFO.

FIFO_WR_PTR (FIFO write pointer) points to where MAX30101 writes the next sample. Every time a new sample is pushed onto the FIFO, this pointer advances. FIFO_RD_PTR (FIFO read pointer) points to where the processor gets the next sample from FIFO. Every time a sample is pushed from the FIFO, this pointer advances. OVF_COUNTER (FIFO overflow counter) counts number of samples lost when the FIFO can no longer accept new samples. It is reset to zero when a complete sample is pushed from the FIFO.

Note: *Often in applications, the user might want to reread their samples from FIFO in case their data gets corrupted. Decrease the value of FIFO_RD_PTR by one to reread the FIFO_DATA register.*

While the FIFO can hold up to 32 samples of data, the FIFO depth can be adjusted depending on the number of (LED) channels used. FIFO can store Green, IR, and Red ADC data. Since each sample consists of three channels and each channel signal is stored as a 3-byte data signal, this equates to 9 bytes of data per sample.

Note: *Reading or burst reading the FIFO_DATA register does not automatically advance it. Similarly, reading bytes after 0xFF does not reset the address pointer to 0x00.*

SMP_AVE (bits 7:5 in 0x08) are used to select number of samples averaged per FIFO sample. Adjacent samples in each channel can be averaged by writing to this.

FIFO_ROLLOVER_EN bit allows the user to update the FIFO. When the FIFO is completely full, room for new data can only be made if FIFO_DATA is read or if FIFO_WR_PTR/FIFO_RD_PTR positions are changed. In this case, the purpose of the FIFO_ROLLOVER_EN bit is that when it is set, the FIFO address rolls to zero and allows new data to fill the FIFO.

FIFO_A_FULL bits allow the user to determine the number of samples in the FIFO by adjusting when to trigger A_FULL interrupt (bit 7 in Interrupt Status 1 register).

Recommended Practices:

- Reset (0x00) FIFO_WR_PTR, FIFO_RD_PTR, and OVF_COUNTER when starting a new heart rate or SpO2 conversion.
- Try to avoid writing to FIFO_WR_PTR, OVF_COUNTER, and FIFO_DATA. They automatically advance when data is inputted by MAX30101. Only FIFO_RD_PTR should be written if needed (to reread samples for instance).

Proximity Detection

Note: *Entering or exiting the proximity mode clears the FIFO. A flowchart (**Figure 28**) is provided for setting up proximity detection. This provides a general guideline and the user should use their own code for implementing proximity detection while keeping this in mind. Although the flowchart stops at "end," it should be noted that "end" means that proximity detection has been verified.*

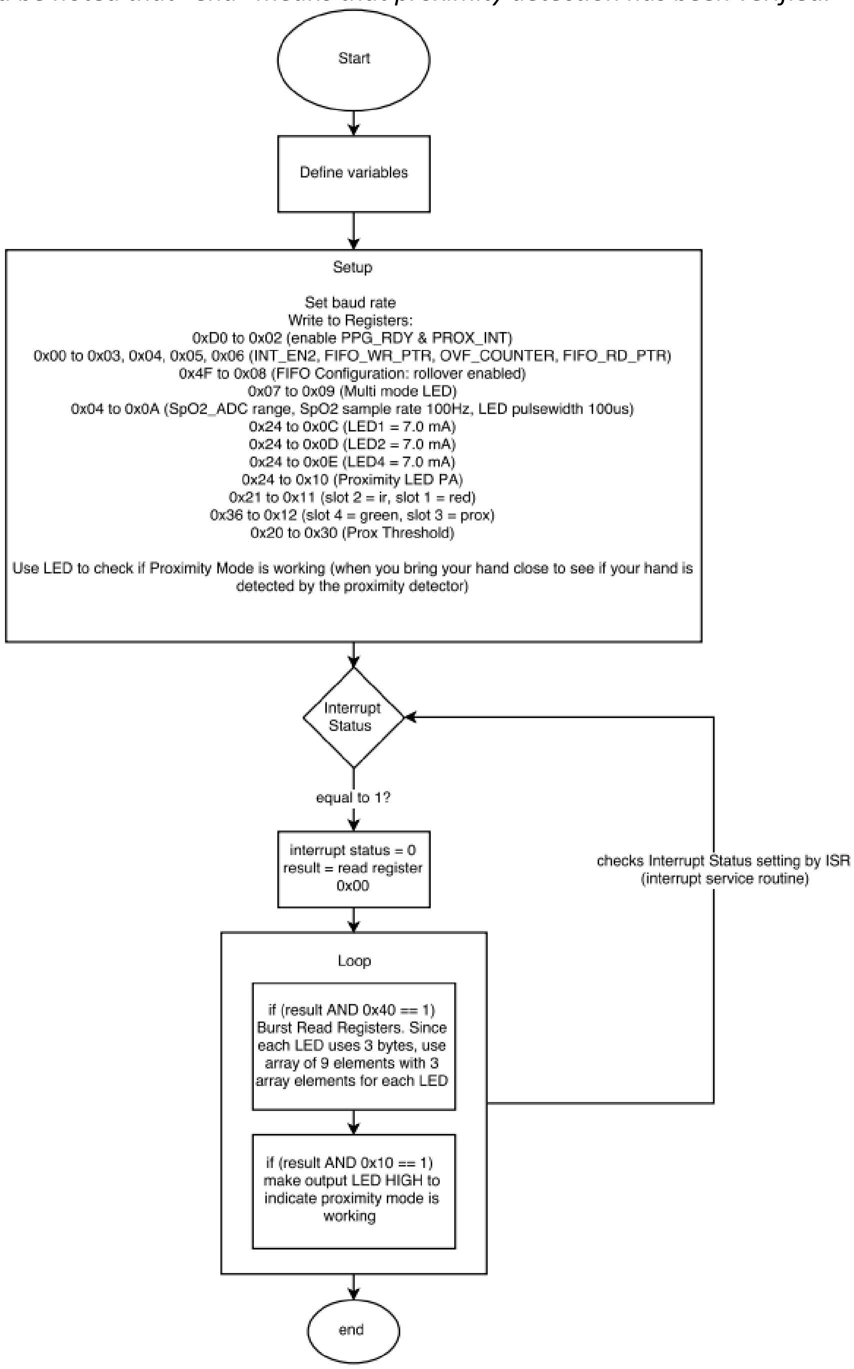


Figure 28. General guidelines for setting up and verifying the proximity detection function.

Note: *Proximity detection usually uses IR for detection, thereby avoiding visual detection of visible light.*

Post-Processing

Post-processing requires several steps which include filtering, peak-to-peak detection, normalization, and digital signal processing. Many users usually want a simpler way of understanding the raw data that they are capturing. A basic method shows the use of the ADC code that is visible in the GUI (**Figure 29**).

Note: *For useful measurements, use the appropriate post-processing techniques.*

Heart-Rate Post-Processing Using ADC Code

Go to the file, choose "log," and save the file. Then, with your finger touching the sensor, click on "start monitor." The heart-rate signal can then be verified visually from the graphical plot on the GUI. Collect the data for a few seconds, then go back to file and click on "log" to finish saving it. Next, open the file in Microsoft Excel, or any spreadsheet software, and graph "Raw data" on the y axis and the time on the x axis. The user should get a graph like the one in **Figure 29**.

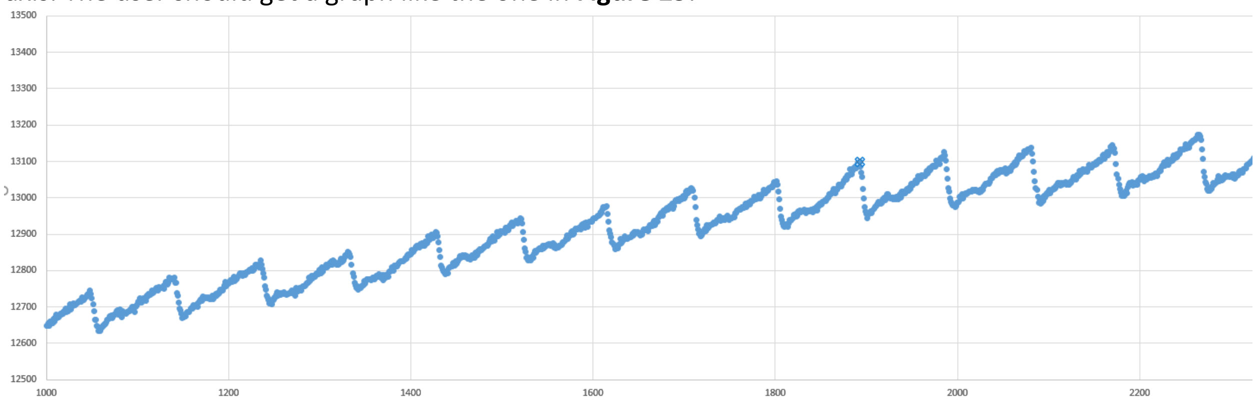


Figure 29. ADC code plotted with respect to time.

One period is shown in **Figure 30**. The numbers 1 and 2 identify the two peaks (1 = systolic, 2 = diastolic) in the signal. Heart rate is found by measuring the time between consecutive systolic peaks and then multiplying it by 60. It should be noted that often the time (on the horizontal axis) is not in seconds which is why the user should convert it before calculating their heart rate. For this example, HR was calculated to be 53 bpm.

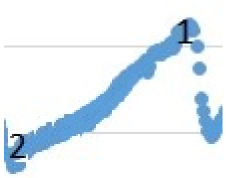


Figure 30. One period of the ADC code plotted with respect to time.

SpO2 Post-Processing Using ADC Code

A similar procedure was followed to log Red and IR data from the GUI. **Figure 31** was plotted in Microsoft® Excel®.

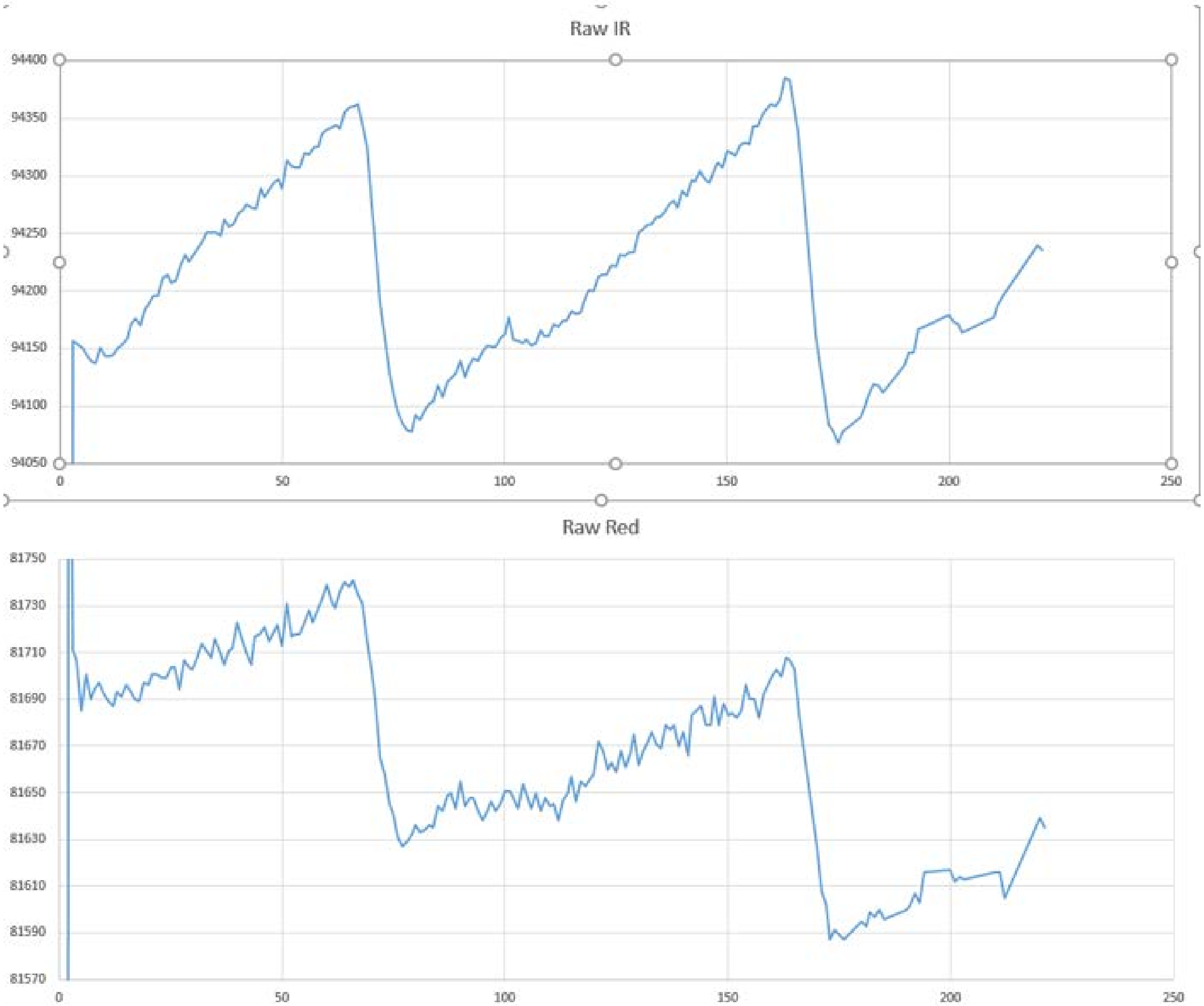


Figure 31. IR and Red Raw data for SpO2 processing.

As mentioned in the *In-Depth Discussion*, DC and AC components should be verified first. The next step is to normalize the two (by taking the ratio of AC to DC) and then finding a value "R," which is the ratio of normalized Red to normalized IR data. Finally, a linear approximation can be used to find SpO2.

In Figure 31, the DC component was found by using a straight-line approximation between two valleys. Let's label the points first. Call the valley between 50 to 100 "1" and the valley between 150 to 200 "3." The peak between 150 and 200 is called "2."

The DC component is the offset of the AC signal, which can be found by first drawing a line between 1 and 3 and then drawing a line parallel to the y axis from 2 to the line connecting 1 and 3. The DC value is the point where the two lines intersect.

The AC component on the other hand is the distance between the peak ("2") and the DC value. These calculations are shown in **Figure 32**.

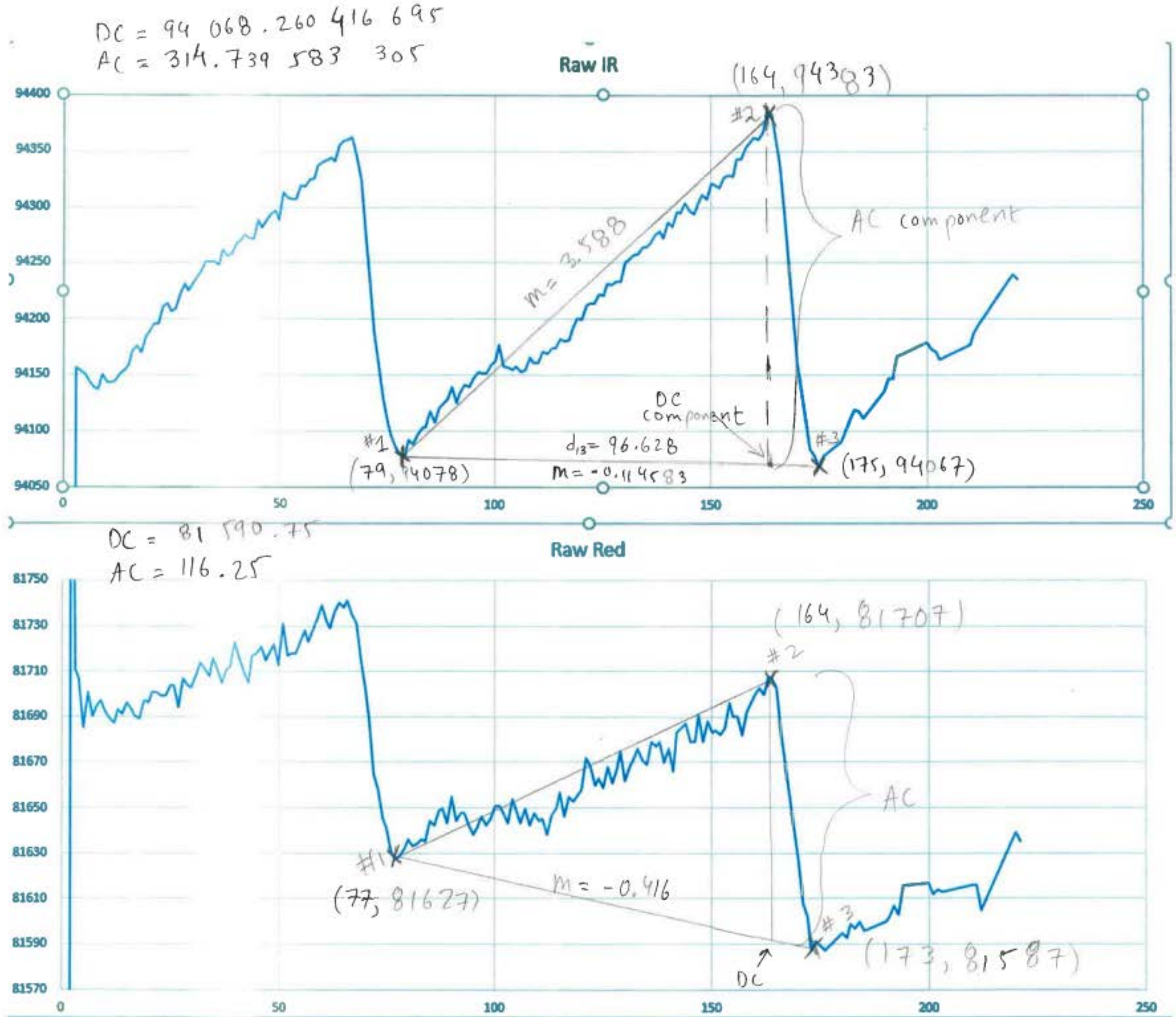


Figure 32. Hand calculations needed for SpO2.

The AC and DC components are labeled above each graph. The following equations were used to first find "R" and then SpO2.

$$R = \frac{\frac{AC_{red}}{DC_{red}}}{\frac{AC_{IR}}{DC_{IR}}} = \frac{\frac{116.25}{81590.75}}{\frac{314.739583305}{94068.260416695}} = 0.42583738237923$$

SpO2 = 104 – 17R = 104 – 17 (0.43) = 96.8%

Enclosure Consideration

Since the MAX3010x is used for optical applications, the user must minimize the amount of ambient light exposure to maximize its performance. Ambient light consists of all the light that is not part of the intended signal (i.e., sunlight, room lights, etc.). Additionally, as the enclosure can be in contact with human skin for long periods of time (e.g., fitness applications), an enclosure made of biocompatible material should be used. It should be kept in mind that while MAX30101 works the best when it is in direct contact with human skin. The enclosure typically incorporates some distance between MAX30101 and skin which causes measurement degradation.

With these factors in mind, the following recommendations are given:

1) Use optical walls to minimize crosstalk between LEDs and photodiodes.
2) Create enclosure designs that minimize ambient light.
3) Use biocompatible materials for the enclosure.
4) Use optical computer simulations to help guide the design of the sensor-tissue interface. The use of optical resins or optical-grade lens films (with air gaps) for water (i.e., sweat) resistance can greatly affect the optical system performance.

Troubleshooting

Firmware

If MAX30101 is disconnected without first exiting the GUI, the firmware on the microcontroller might get corrupted. This can be confirmed by disconnecting and then connecting the microcontroller. If the two lights (green and red) on the microcontroller do not turn on or if they keep flashing without stopping, then the firmware might be corrupted. In this scenario, the firmware must be reflashed and tested again using the GUI. The suggested software for this operation is Silicon Labs Flash Programming Utility. It is not provided with the EV kit but can be found on the Silicon Labs website.

A step-by-step procedure is shown in **Figure 33** for reflashing firmware by connecting a Silicon Labs USB Debug Adapter to pins (J2) and PC. It should be noted, however, that if the pins (J2) are not provided, as they are removed sometimes when packaging the microcontroller in an enclosure, the user cannot flash new firmware.

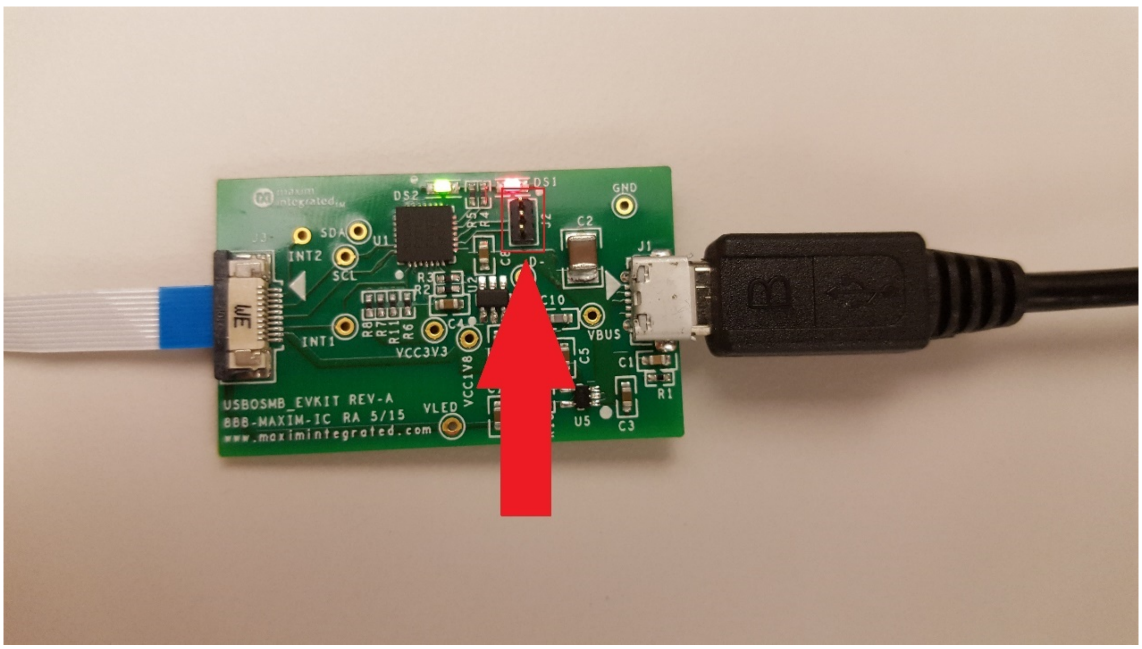


Figure 33. Where the USB Debut Adapter should be connected for reflashing.

Download Silicon Laboratories Flash Utility (**Figure 34**).

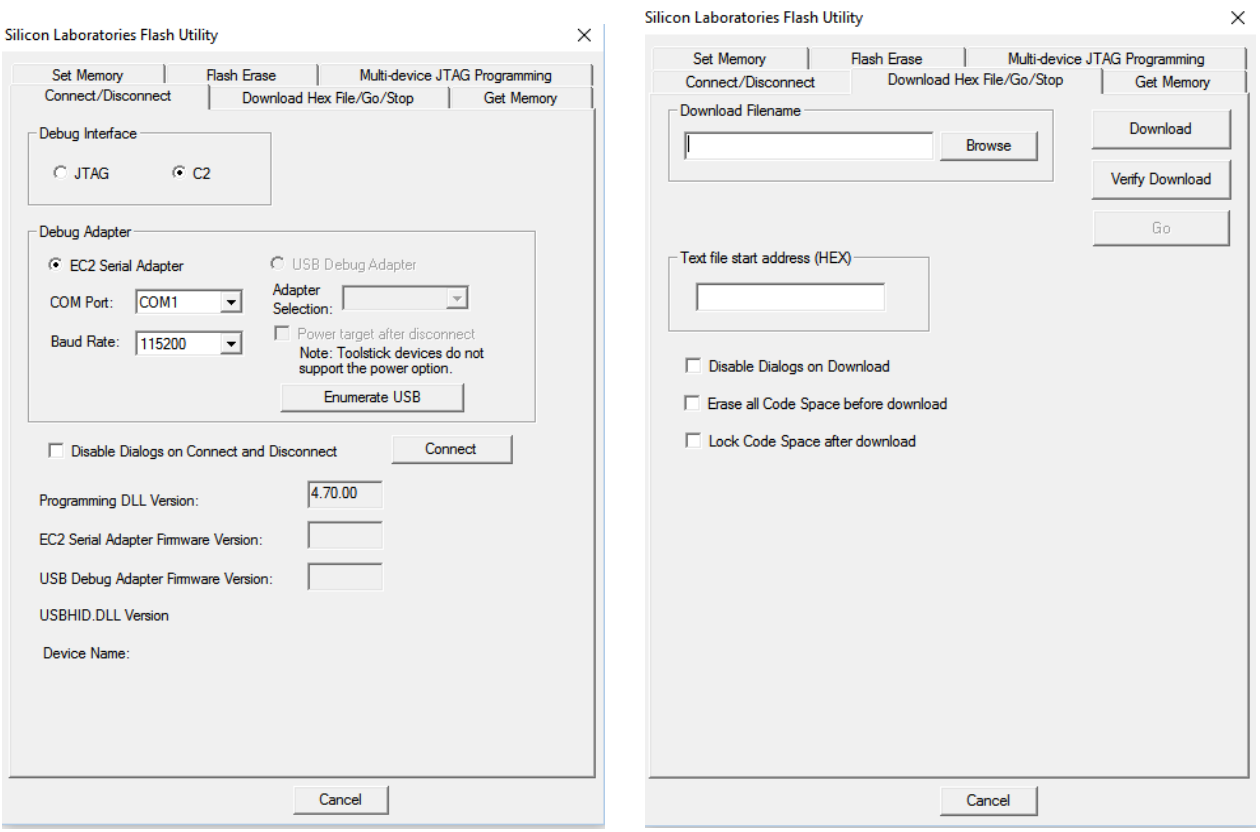


Figure 34. Silicon Laboratories Flash Utility.

The following steps flash the firmware on the microcontrollers:

- **Enumerate USB** (since Silicon Labs USB Debug Adapter is being used).
- Select **USB Debut Adapter**.
- Select **Connect**.
- Click on the tab **Download HEX File/Go/Stop**.
- Browse and select the hex file for firmware.
- Select **Download**.
- Go back to the tab **Connect/Disconnect**.
- Select **Disconnect**.

Ambient Light

Sometimes the ambient light in the room can also affect the HR-SpO2 measurements. The flickering of lights in a room or light coming from a monitor or laptop can contribute noise to the intended measurement.

The 'spikes' that can be seen below are characteristic of flickering lights. As such, if the user notices a regularity in spikes in the intended signal (**Figure 35**), they should try to go in a darker room or cover MAX30101 to minimize the ambient light. For comparison, **Figure 36** shows what the signal would look like if MAX30101 was used in a completely dark room.

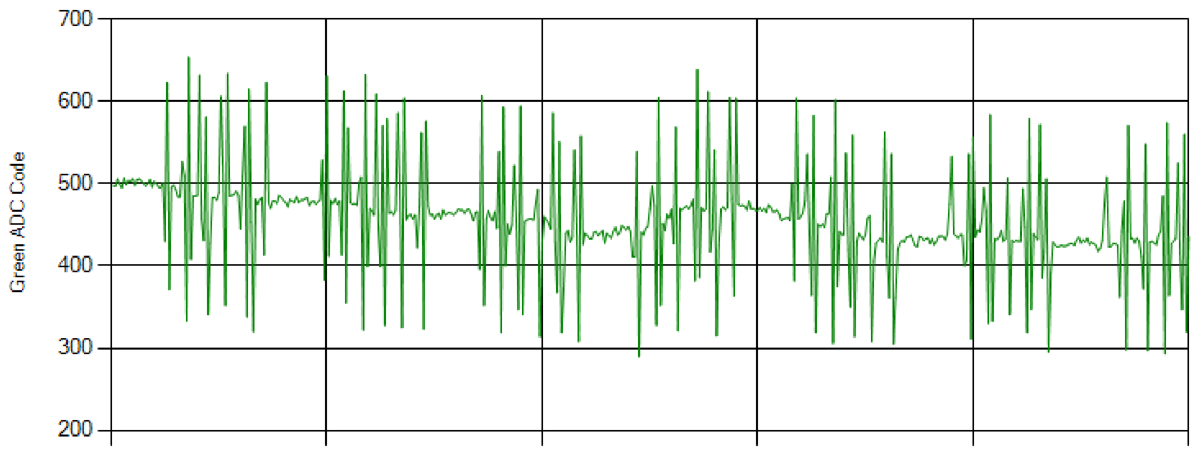


Figure 35. Regularity in spikes indicating possible ambient light.

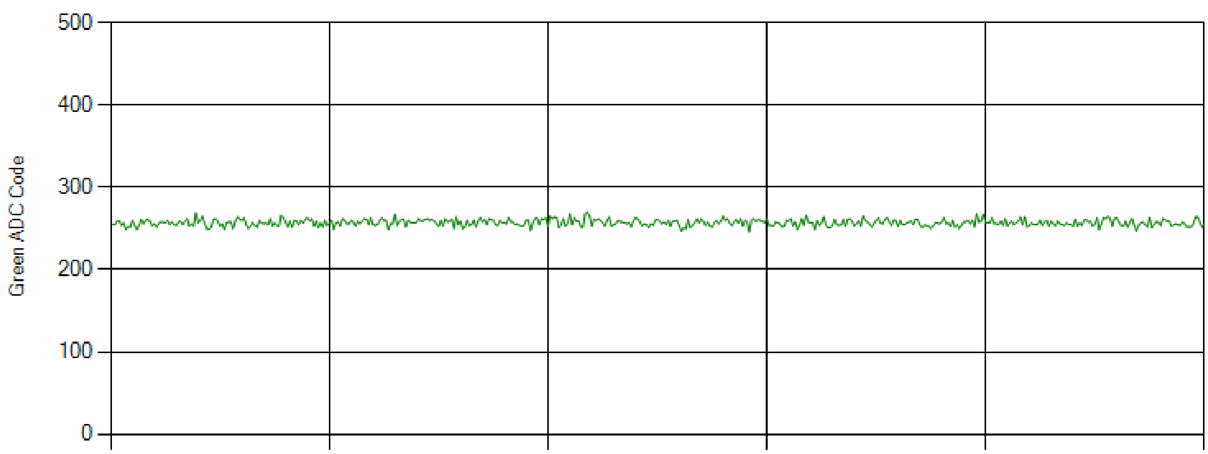


Figure 36. No spikes and low-ADC code indicating a dark room.

References

[1] Wukitsch, M. W., Petterson, M. M. T., Tobler, D. R., & Pologe, J. A. (1988). Pulse oximetry: analysis of theory, technology, and practice. *Journal of Clinical Monitoring*, *4*(4), 290-301.

[2] Rusch, T. L., Sankar, R., & Scharf, J. E. (1996). Signal processing methods for pulse oximetry. *Computers in biology and medicine*, *26*(2), 143-159.

[3] Tabulated Molar Extinction Coefficient for Hemoglobin in Water, Scott Prahl, http://omlc.org/spectra/hemoglobin/summary.html

[4] Vizbara, V., Solosenko, A., Stankevicius, D., Marozas, V. (2013) Comparison of green, blue, and infrared light in wrist and forehead photoplethysmography.

Figures

Figure 1: J. G. Webster, "Design of Pulse Oximeters", Series in Medical Physics and Biomedical Engineering, Taylor & Francis, New York, USA, 1997.

Trademarks

Excel and Microsoft are a registered trademarks and Microsoft is a registered service mark of Microsoft Corporation.