

**OB1203**

**OB1203 Heart Rate, Blood Oxygen Concentration, Pulse Oximetry, Proximity, Light and Color Sensor: Signal to Noise Ratio**

**Abstract**

This application note describes reflective mode photoplethysmography (PPG) measurement and how to measure the signal to noise ratio for the IDT OB1203 all-in-one optical biosensor with proximity and RGB color sensing capability.

In this application note we describe the relevant signal frequency range for human body PPG and describe signatures of typical internal and external noise sources.

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## 1. Application Circuit

It is suggested to use low noise power supply sources, such as low-noise low dropout (LDO) linear regulators. Independent supplies for analog and digital supply (VDD) and LED supply (LED\_VDD or LVDD) are suggested. Pull-up resistors in the appropriate range to microcontroller logic voltage of 1.8–3.3V are necessary for I2C SDA, I2C SCL and INTB pins. A decoupling cap between VDD and analog ground (GND) of 0.1µF and optionally 1µF for longer leads is suggested. 4.7–10 µF capacitors are useful between LVDD and LED\_GND (LGND). The analog ground (GND) and LED power ground (LGND) should be connected at a low impedance node to avoid ground bounce effects when the LED current is high. Trace lengths should be minimized and wider trace/via widths used for current carrying LVDD and LGND lines. All the LED pins should be connected to a low thermal impedance pad.

For bench test functionality purposes it is sufficient to connect LVDD and VDD to 3.3V source relative to LGND and GND, and connect the I2C and INTB lines to the logic level (typically 1.8V or 3.3V) via pull-up resistors in the appropriate range. Note that the internal digital and analog levels are set by an internal LDO regulator.

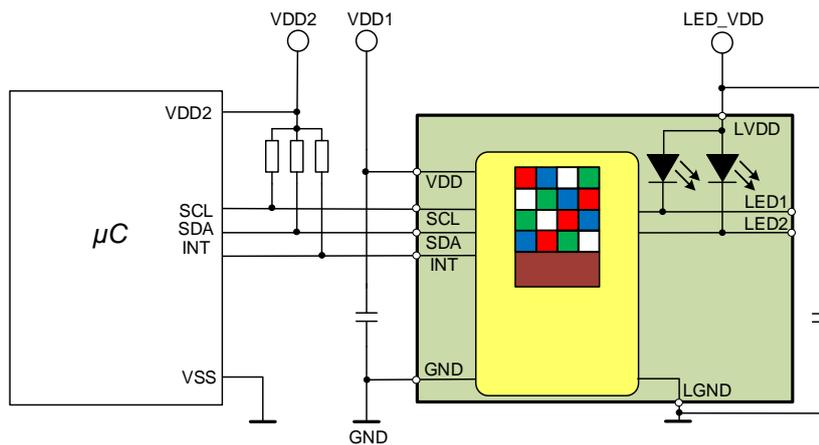


Figure 1. Application Circuit

## 2. Physiological Mechanism of Reflective PPG

### 2.1 Photoplethysmography (PPG)

PPG is the measurement of the transmission of light through living tissue. A time series contains a DC component related to the experimental setup and an AC component related to time-varying changes in tissue transmission, for instance, due to arteriole dilation after a heart contraction or related mechanical changes in tissue fluid content. PPG can be measured with any of several wavelengths such as infrared 850–950 nm, red 630–680 nm, or green 530–560 nm, typically by an LED or laser diode and a receiver photodiode. There are two common types: transmissive and reflective.

### 2.2 Reflective versus Transmissive PPG

Transmission PPG is measured through the top of a fingernail to the bottom of a finger, or toe, or ear with emitter and receiver on opposite sides facing each other. The most common measurement is via a finger clip (Figure 2). The light transmission through the finger exhibits a pulsile waveform with a fast rise (blood in-rush) and slow ramp down, and a dichrotic notch arising from the reflection of the heart contraction pulse from the extrema of the artery.

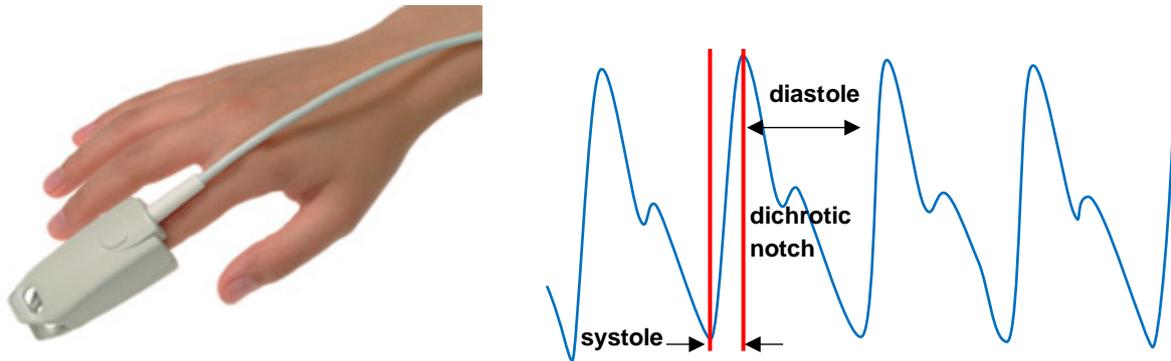


Figure 2. Finger Clip-based Transmission PPG

Figure 2 (left): Fingerclip-based transmissive PPG measurement. Figure 2 (right): Typical transmission PPG signal with the systolic period typical of blood in-rush, the diastolic period of relaxation, and the dichrotic notch arising from pulse reflection.

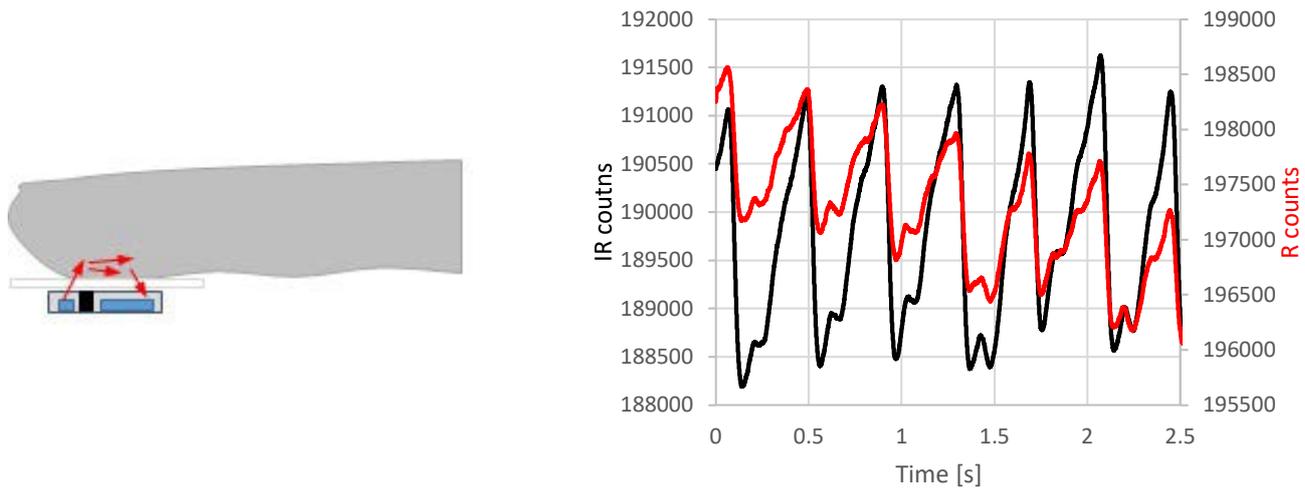


Figure 3. Reflective PPG

Figure 3 (left): Reflection-based PPG measurement method. Figure 3 (right): Typical reflective PPG signal. Note the fast negative systole slope and the dichrotic notch following close afterward followed by slow positive diastole relaxation. The amplitude of the AC signal can be estimated as the peak height above a line between adjacent PPG waveform minima.

Reflective PPG is measured against the skin with emitter and receiver on the same side, similar to the emitter and receiver arrangement of an active infrared (IR) proximity sensor (Figure 2). There is some disagreement between experts on the mechanism of reflective PPG signal, however a suitable explanation is provided by Prof. [Kamshilin](#)<sup>1</sup>, "...pulsatile transmural pressure of the arteries, which compresses/decompresses the density of capillaries in the dermis, thus modulating the blood volume in the capillary bed, which in its turn modulates the power of remitted...light."

According to this model, the outer tissue of the finger is mechanically squished between the sensor window and the expanding arteries and arterioles deeper in the finger. This pressure pushes light absorbing blood out of the dermis layer, similar to how pushing on a finger briefly will cause the skin to appear whiter. Thus, the observed reflective "whitening" PPG signal is inverted relative to the transmissive PPG signal which sees an increase of blood absorption during the high pressure phase of the PPG waveform. Reflective PPG shows a fast decrease and slow rise (Figure 2).

Accordingly, consistent, light finger pressure is ideal for reflective PPG measurements. Likewise, reflective PPG measurement, while convenient in mobile devices, may not be optimal for individuals with very soft fingers including young children and some elderly individuals or individual with thick callouses on the skin.

The transmission PPG waveform origin has two parts: the traditionally referenced swelling of arteries and arterioles under pressure as well as [disaggregation of blood cells under higher flows](#). However, these effects are not dominant signals in reflection PPG, due to the previously mentioned tissue mechanical modulation being a larger source of signal variation.

The observed signal has a large static or DC component on which the small AC cardiovascular signal appears. The ratio of AC/DC is relative to tissue perfusion and depends on several details. Notably, the closer the emitter and receiver the lower the modulation of the signal due to the heartbeat (shorter absorption path length) and the higher the DC "crosstalk" component.

<sup>1</sup> Alexei A. Kamshilin and Nikita B. Margaryants, "Origin of Photoplethysmographic Signal Waveform at Green Light", *Physics Procedia* 86 (2017) 72-80.

A very compact measurement is also more sensitive to finger position and motion. With the addition of a masking ink layer on the inside of the window to form apertures, received light further decreases. For these reasons, a small form factor PPG sensor in a mobile device requires high dynamic range, sensitivity, and a noise-tolerant algorithm.

### 2.3 SpO<sub>2</sub> Mechanism

Measurement of the saturation of blood by oxygen is accomplished with PPG measurements at two wavelengths, taking advantage of the differential absorption of oxyhemoglobin and deoxyhemoglobin. The most common wavelengths are red and IR, due to the strong differential absorption, availability of light sources, relatively flat spectra (for wavelength shift tolerance). The IR signal changes little with oxygenation of the blood, whereas the red signal changes strongly with oxygen content. At a rudimentary level, the IR signal is like a baseline against which changes in the red signal can be compared to estimate blood oxygenation in the peripheral finger tissue.

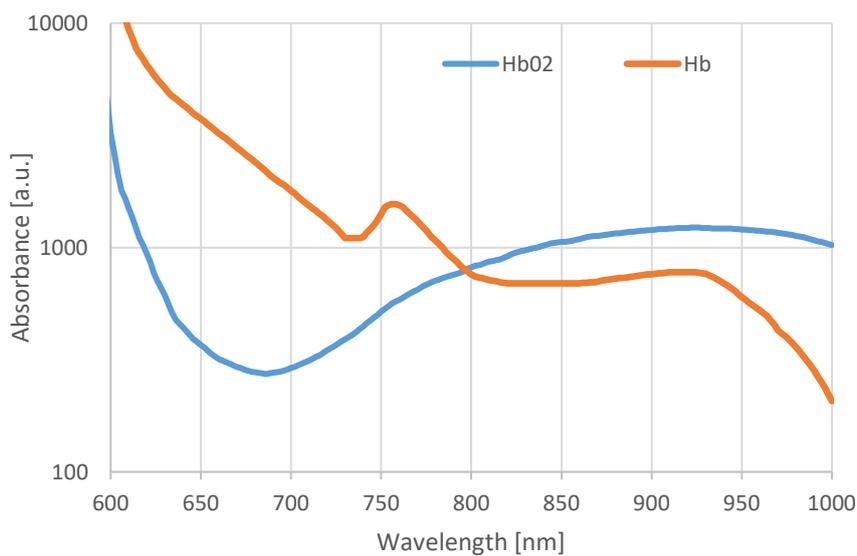


Figure 4. Absorbance Spectra for Oxyhemoglobin (HbO<sub>2</sub>) and Deoxyhemoglobin (Hb)

The blood Oxygen saturation level or SpO<sub>2</sub> level is calculated from a calibrate curve plotting SpO<sub>2</sub> versus the “ratio of ratios” called the “R curve” which is done by measuring against a known instrument or blood test reference in a hypoxia lab using breathe down testing under the direction of a physician.

The “ratio of ratios” takes into account the variation in signal amplitude from person to person in the following way. The DC component has PPG-irrelevant information such as surface reflections and skin tone. However, it does set the scale for the AC signal due to hemodynamics of interest. Therefore, the red channel AC signal (measured by high pass filtering the data) is normalized by the red DC signal. The IR channel AC signal is normalized by the IR channel DC signal and the ratio of those two normalized values contains information unique to the blood Oxygen saturation level for this particular system. If anything in the mechanical design of a product changes—even its color—the calibration procedure must be redone.

$$\text{Eq. 1: } R = \frac{R_{AC}/R_{DC}}{IR_{AC}/IR_{DC}}$$

SpO<sub>2</sub> requires a much higher SNR than heart rate because we are not merely trying to detect the heartbeat which is a small ripple on a big background, we are trying to quantify the size of that ripple and divide it by another very small ripple. Tight control of red LED wavelength, or wavelength-specific calibration is important. In addition, artifacts due to finger motion should be identified and removed from the data or compensated.

### 3. Measurement Bandwidth and Signal Level

For SpO<sub>2</sub> biological signals of interest are in the 0.3–13 Hz range. Tissue acts as a low pass filter and frequencies higher than about 13Hz are not observed. However, since we can't guarantee that one of our samples will be the peak or valley, typically sampling is done at many times the minimum bandwidth in order to best time-resolved the peaks and valleys, usually at least 100 samples per second (sps). Also, rapid sampling is used in combination with a digital low pass filter (e.g. averaging) to improve SNR (Signal to Noise Ratio). On the low frequency side, we have a baseline (DC) signal which drifts due to a variety of sources including a variation of finger pressure against the sensor. The DC baseline is typically tracked/updated with a time constant similar to one heart beat, such that by subtracting the baseline we can observe a regular PPG signal that appears to swing around zero.

In a simple example, the DC signal is the time average. Any linear slope due to gradual physiological changes or LED temperature change is fit by regression and removed. Then the AC signal amplitude could be estimated as the difference between a systole valley and the nearest the diastole peak (Figure 2). For this reason, drift of signal amplitude over time scales longer than one heart rate does not impact the SNR negatively. Each period of AC amplitude estimate is referenced to its own DC signal. Since human hearts beat in the range > 40 beats per minute (BPM), noise or drift in the range < 0.3Hz does not impact SNR significantly for typical algorithms. Indeed, the experimental drift due to physiological effects like breathing and muscle movement and perfusion change due to constant pressure can dominate over longer time scales.

As PPG signals are quasi-static (roughly the same DC level over time), signal distortion is not considered, hence SNR is used rather than SINAD (Signal to Noise and Distortion ratio). ADC integral nonlinearity (INL) is similarly largely inconsequential provided the LED driver power is set to keep the red and IR power levels at a similar level for each measurement. If the INL or DC signal level were inconsistent over devices such variations would affect the R value and SpO<sub>2</sub> accuracy.

The IR and red LED current levels can be independently set by a high resolution current DAC to adjust the DC signal to a desired level prior to data collection via an appropriate search or AGC loop. During a measurement it is usually no necessary to adjust the LED current levels unless a large motion causes the signal to exit an allowed range. In an example the target signal level to exit the AGC control loop may be 75 ±5% and the allowed range during a measurement may be 60–90%. Exiting the allowed range reactivates the AGC loop. Note that larger signals are preferred to maximize SpO<sub>2</sub> resolution.

### 4. Measurement Noise Sources

The following is a short list of typical sources of noise for reflective mode PPG

- Natural heart rate variation (HRV)
- User movement (voluntary and involuntary)
- ASIC supply voltage noise (VDD)
- LED supply voltage noise (LVDD)
- Ambient light variation (flicker)
- Transmitter noise (LED driver)
- Receiver measurement noise (photodiode+amplifier/ADC)

The respective noise sources are discussed briefly in the following sections.

## **4.1 Heart Rate Variation**

Heart rate changes during the breathing cycle according to a process known as respiratory sinus arrhythmia. This is one method of detecting breathing rate. Also, subconscious oscillations known as Traube-Hering-Mayer waves are observed with an approximately 10 second period. Suppression of heart rate variation is attributable to stress, which triggers a steady, elevated “fight or flight” heart rate.

## **4.2 User Movement**

User movement can be voluntary, but is often involuntary tremors. Improved stability is obtained in finger clip transmissions methods in which the user is not required to apply pressure. In reflective techniques, it is desirable to have an arrangement in which the pressure is as constant as possible. For instance, the sensor can rest on an upturned finger with gravity providing the pressure. Or, the position of the finger or hand may be such that its weight applies a steady pressure. Avoid long extensions of the arm to the sensor as the lever effect will amplify small movements into larger pressure variation. Note that the wider the field of view of the sensor, the less sensitive the measurement is to motion artifacts. Restricted fields of view through apertures in a cover glass will be more susceptible to motion artifacts as tissue is not necessarily homogenous in the field of view.

Where a fixed target is used for SNR measurements, special care must be taken to avoid pickup of acoustical noise and vibrations. The target must be rigid, fixed relative to the sensor and not sensitive to vibration. A high resolution PPG sensor is an effective acoustic vibration transducer, so ambient noise such as fans and HVAC systems, or desks prone to vibration such as a sit-stand work station or platform on a long supporting armature should not be avoided for SNR measurements.

## **4.3 ASIC Supply Voltage (VDD) Noise**

Ideally the ASIC power supply is independent from the LED power supply, for instance via a separate LDO regulator with bypass capacitors. The relevant specification for translation of VDD noise into signal noise is the VDD power supply rejection ratio (PSRR). Typically the ASIC internal LDO will provide improved PSRR with additional voltage overhead over the minimum VDD. If the LED ground (a.k.a digital ground) path is connected to the VDD ground at a node which has finite resistance to the system ground, then the VDD ground can float up when the LED current is high causing an apparent reduction in signal. This is called “ground bounce” and can be reduced, if necessary, by separating LED/digital and analog grounds and connecting them only at a low impedance node. Ground bounce scales the AC and DC signals equally, so such changes are cancelled by division in the SpO<sub>2</sub> calculation. The effect of ground bounce may be more important for proximity measurements than for bio measurements as offsets due to ground bounce can reduce linearity at low signal levels.

High frequency supply noise should be bypassed with a 0.1µF capacitor to ground and additional 1µF capacitor if leads are longer than a few centimeters or other noise sources are present.

Additionally, boards should be designed to prevent pickup of I<sup>2</sup>C and INTB signal switching on the VDD supply. Lower logic levels (1.8V) produce less interference.

## **4.4 LED Supply Voltage Noise**

Power supply rejection ratio (PSRR) scales with the voltage drop in the driver. Thus, a higher supply voltage will offer improved PSRR for a fixed current level. Note that the overhead voltage depends on the LED forward voltage, which is higher for red and the infrared. The LED supply voltage should be from a sufficiently low impedance source, e.g. an LDO and buffered by a capacitor in the 4.7–10 µF range, or else powered from the battery.

## **4.5 Ambient Light**

Ambient light adds two sources of noise. Large photocurrents are subtracted by the ambient light subtraction circuitry. However the current itself has electronic shot noise. Therefore, large ambient light currents increase receiver noise. The second type of noise which is typically more challenging is rapidly changing ambient light, often called “flicker” noise. This is due to AC power frequency (100Hz or 120Hz), electronic dimmers, or LED PWM modulation. (This is not the electronic “flicker” noise in a MOS transistors.) OB1203 has two levels of ambient light suppression, however large amplitude, and especially high frequency modulation can add intolerable noise to a reflective PPG measurement. For 50Hz environments, sampling at a multiple of the power frequency is possible, providing a sinc filter for convenient for removal of power frequency flicker in incandescent lighting.

## **4.6 Transmitter Noise**

As with any closed loop system such as RADAR, LIDAR, or SONAR, uncorrelated transmitter noise sets the measurement noise floor. Transmitter noise scales with the LED current and/or received signal level. Some types of ADC noise, such as ADC reference current noise, scale with ADC counts and behave similarly to transmitter noise.

OB1203 transmitter noise is a function of the LED driver current level. Larger drive currents produce a more stable control loop. Drive current register settings larger than 0x0FF (255) should be used to avoid excess transmitter noise from limiting the SNR, and the largest possible driver current should be used in any case.

## **4.7 Receiver Noise**

Receiver noise includes photon shot noise, amplifier noise, ADC noise and quantization noise. Receiver noise scales with receiver (ADC) gain since gain amplifies noise as well as signal. At a fixed gain setting receiver noise is approximately constant, therefore maximum SNR is achieved near the full scale range. To avoid potential saturation or affects from potential device variation of INL it is desirable to operate the LED such that received power between about 60-80% of full scale.

OB1203 receiver noise is a function of two parameters: the ADC gain and the signal level. For maximum SNR the ADC gain 1 mode should be used. Higher gain amplifies both noise and signal similarly. Noise increases slightly with increasing signal levels due to signal-dependent ADC and transmitter noise contributions, although overall SNR improves with increasing signal level.

## 5. OB1203 Noise Measurements

Measurements of transmitter and receiver noise are made using a fixed partially reflective target such as a 90% (diffuse) reflective target.

OB1203 SNR for individual ADC conversions in gain 1 mode is typically 3500, 11.8 bits, or 71dB in a 0.3-50Hz bandwidth, i.e. 3 seconds of data at 100 sps. In this case, performance is limited by noise which scales with signal, so SNR is more appropriate than effective number of bits (ENOB) for understanding achievable system performance. Receiver noise is about 21 counts RMS for max SNR of 12,600, 13.6 bits or 82dB in gain 1 mode, or about 21 counts RMS.

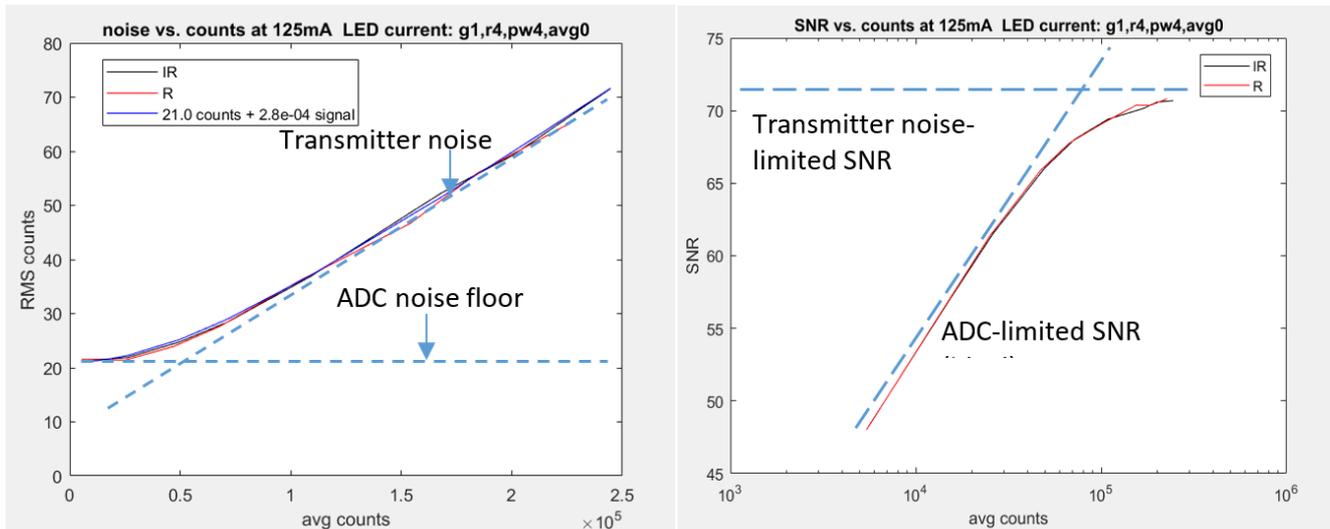
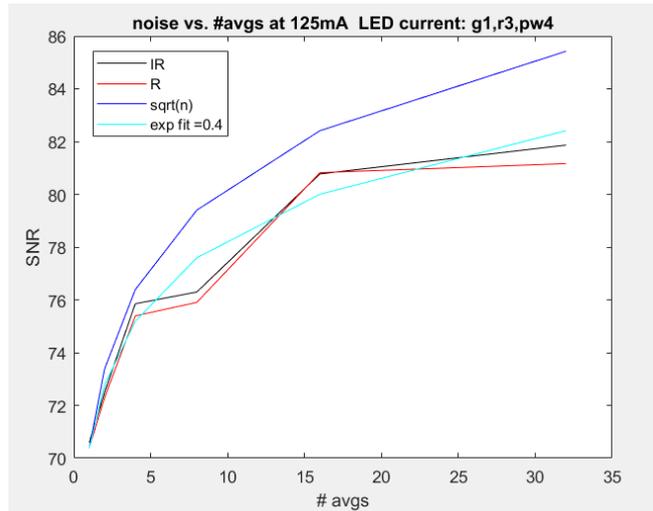


Figure 5. SNR vs. Signal Level

Figure 5: (left) Signal-dependent rms noise characteristics for IR (black), far red (red) and fit (blue) versus AC average count, measured by changing the distance to a static reflecting target. The fit =  $21 + 2.8 \times 10^{-4} (ADC_{counts})$ . Dashed lines show asymptotic behavior and low and high count levels. (Right) SNR versus count level on a logarithmic scale. Measurements settings are ADC gain 1x, period 0b100 (2.083ms), and pulse width 0b100 (206 $\mu$ s) in 60Hz mode with 0 averages on-chip.

Measured closed loop system SNR in the 0.3–13Hz bandwidth is about 16,000, 14bits, or 84dB.

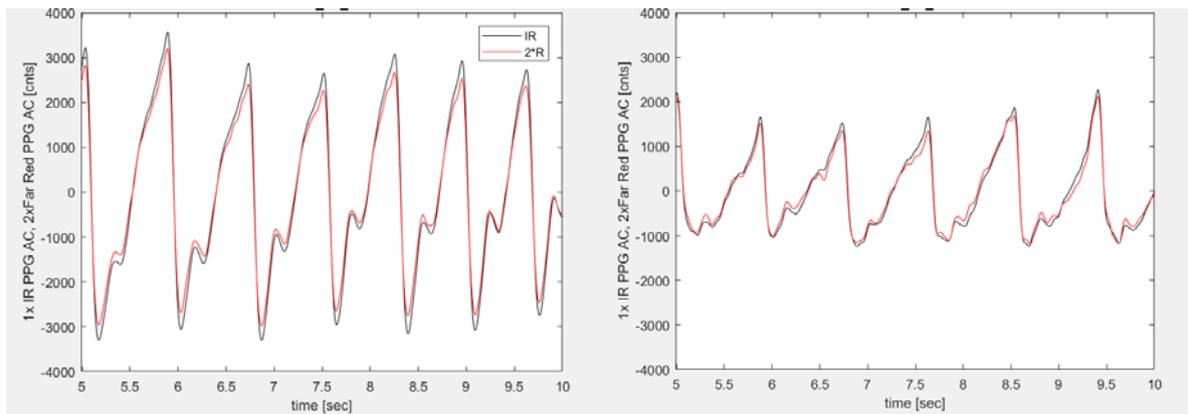
SNR improvement is possible using averaging of multiple samples. When averaging is used, the overall rate of data recorded in the FIFO is reduced by the number of averages performed on the chip. For OB1203  $SNR \sim (\text{number of averages})^{0.4}$ . Reduction from the ideal averaging of independent samples in the presence of white noise where  $SNR \sim (\text{number of averages})^{0.5}$  is nominally due to finite circuit 1/f noise. Where possible, the maximum number of averages should be used. For example, if the desired data output rate is 100Hz, choose 50Hz mode, sample period 0.625ms (1600sps) and 16x averaging. If the desired data output rate is 120Hz, choose 60Hz mode, sample period 0.0521ms (1920sps) and 16x averaging.



**Figure 6. SNR vs. Number of Averages**

SNR vs. number of on-chip averages measured with ADC gain 1x, period 0b011 (1.042ms), and pulse width 0b100 (206 $\mu$ s) in 60Hz mode and variable number of averages. (Note that 8 averages corresponds to 120sps for this setting. Alternatively, 16 averages can be obtained at 120sps for sample period 0.521ms and pulse width 108 $\mu$ s, or at 100sps for 50Hz mode.) Error in SNR estimation is due to a finite sample size. Blue line is ideal averaging (exponent =  $\frac{1}{2}$ ). Cyan line is a fit with exponent = 0.4. Non-ideal averaging is due to non-white (e.g. 1/f) noise spectrum.

SNR is not strongly influenced by the LED pulse width as noise is not receiver SNR-limited. Therefore, short LED durations may be used to reduce the sensitivity to ambient light and allow rapid averaging, without sacrificing much SNR.



**Figure 7. Typical PPG AC Signals: IR and 2x Red**

Typical PPG AC signals obtained from live subjects from the finger for (left) high perfusion and (right) low perfusions with an FFT-based digital top hat bandpass filter in the range 0.3–13Hz. Red AC amplitude is scaled by 2x for visibility.

## 6. Revision History

Revision	Date	Description
1.1	Apr.30.20	Redefined document title.
1.0	Apr.14.20	Initial release.

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