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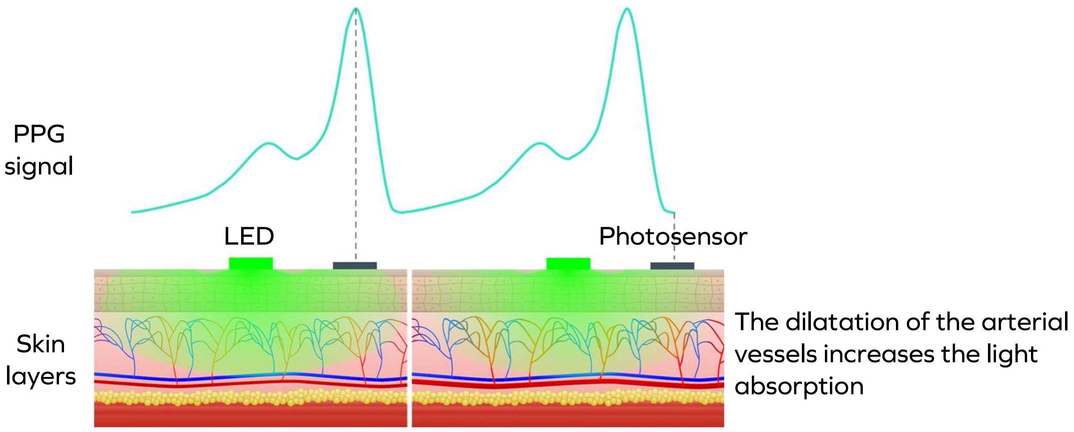
Integration of Stromboli into Consumer Wearables

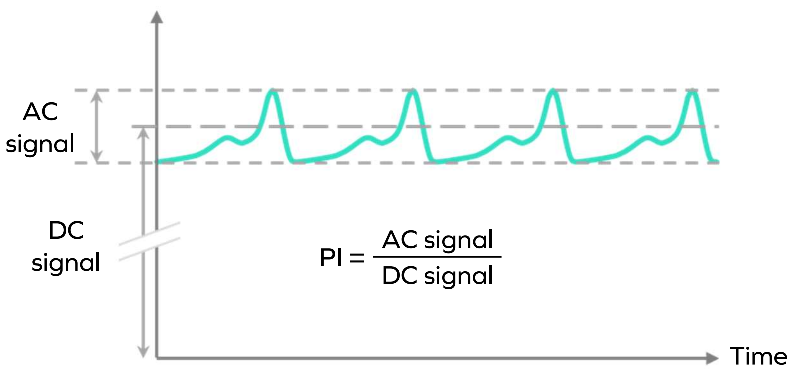
This document introduces the required concepts of photoplethysmography (PPG) and differences relating to PPG signals at different body locations. Suggestions are provided for the integration of the Stromboli PPG module into different wearable devices.

Photoplethysmography

PPG technology relies on the propagation of light into the skin. When the light diffuses into the tissue, a portion is absorbed at a level that fluctuates with the dilatation of the arterial vessels, induced by the heart beats. A photodetector or sensor detects the light reflected from the tissue and transforms it into a photogenerated current.



The variation of the light absorption is a small fraction of the averaged reflected light, resulting in a PPG signal with two components: a large quasi-DC component corresponding to the light diffusion through tissues and non-pulsatile blood layers, and a small AC component due to the diffusion through the arterial blood. One of the main challenges of PPG systems is to maximize the ratio between the two components, the so-called perfusion index (PI). Compensating for a low PI while keeping a good peak-to-peak signal requires an increase in the optical power and/or a sensor with a large dynamic range to avoid saturation. Both approaches result in an increase of the power consumption of the PPG system.



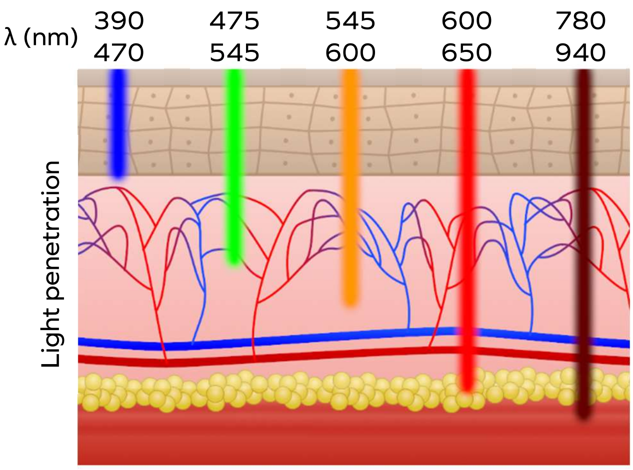
Typical PI values range from 0.5 to 5%, depending primarily on the temperature, body location and on the skin tone.

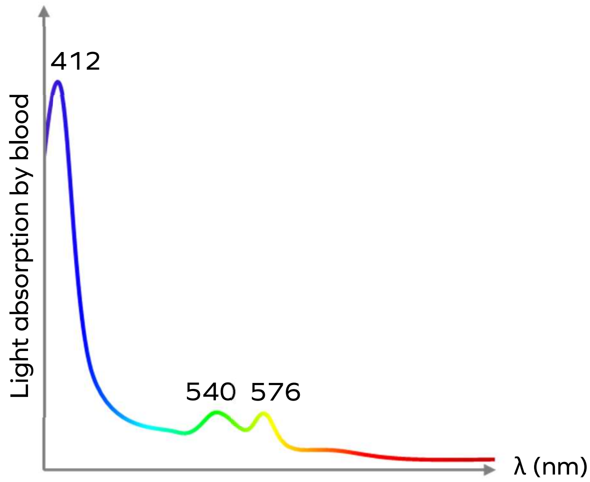
The location where the signal is measured should ensure good perfusion by the blood vessels in the skin. Even though there are several body locations where a good PPG could be achieved, this document focusses only on the most common ones used within consumer devices:

- The ears
- The fingers
- The wrists

Optimizing the distance between the sensor and the light source (known as the SL distance) comes with some trades-off. The bigger it is, the more optical power is required, resulting into a larger power consumption. A larger SL distance also reduces the signal-to-noise-ratio (SNR) of the AC component at a constant optical power. Too small of an SL distance may adversely affect the sensor's effective dynamic range and SNR, due to light reflected from the skin surface. Furthermore, except from smartwatches, most consumer devices accommodate large SL distances.

For a given LED power, the longer the wavelength, the deeper it diffuses in the body. That doesn't mean a better efficiency, as the absorption by the blood decreases as the wavelength increases. That's why the green wavelength is usually chosen as the best trade-off between its capacity to propagate in the skin and being absorbed by the blood vessels for reflective PPG (when the light and the sensor are facing a same direction). In the case of a transmissive PPG (the light and the sensor are facing each other the skin and blood vessels in-between), the red and NIR infrared may be used.





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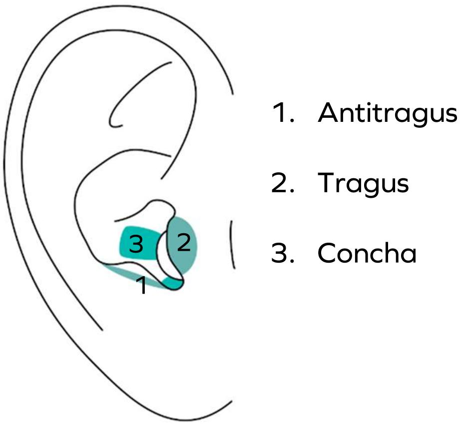
Potential PPG Sensor Locations

Ears

In terms of SNR, the ear is among the best locations to sense a PPG signal. This location is highly vascularised and is less prone to motion artifacts than the finger or wrist. The ear location also features good temperature stability, ensuring consistent perfusion over the time.

Three possible positions for PPG sensing in the ear can be considered:



In most cases, the movement of the earbud within an ear is in the vertical direction. This makes the antitragus ideal for a standing or seated person, as this position will be less prone to motion artifacts and gravity naturally creates a small pressure between it and the earbuds. It is therefore the most common location for a PPG sensor in earbuds.

The tragus is generally a good PPG sensing location, in part a result of the pressure exerted by the sleeve wing of many earbuds against the antihelix, which results in good positional stability. Depending on the shape of an individual's ear, it may be harder to maintain good contact with this location and it is recommended to have the sensor as deep as possible.

The concha is typically a more complex sensing surface, and is more prone to motion artifacts degrading the PPG signal. When lying down, the type of motions changes and it could reduce the motion artifacts.

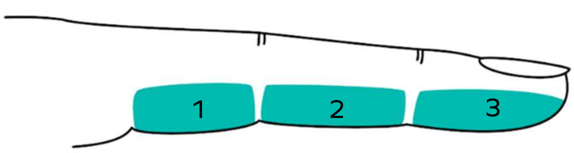
To improve the SNR, two or more sensors per ear can be considered, for example, in both the tragus and antitragus. This solution is beneficial due to the near-opposite positions allowing continuous contact from at least one the sensors at a given time. It also provides more resilience in dealing with variations between ear physiognomy. For some users the tragus can provide better PPG signals than the anti-tragus, or vice versa.

Fingers

This location provides for a high-SNR PPG signal. Fingers are highly vascularised tissues, but tend to suffer from low perfusions resulting from low-temperature conditions. Fingers are much more prone to movements and the resulting motion artifcacts in the PPG signal. Specific use cases, like sleep monitoring, accompanied by the possibility of having a tightly fitting device, such as a ring, can compensate for these downsides.

The finger location is also more suitable when the device must be set up by someone other than the user, as in many medical situations.

The following figure highlights the possible locations to have a PPG sensor on a finger.



1. Proximal phalanges
2. Intermediate phalanges
3. Distal phalanges

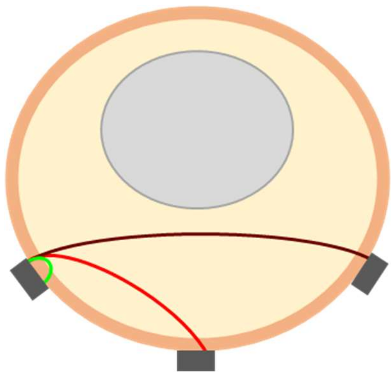
These locations will generally give a similar PPG SNR. But the PPG signal is extremely sensitive to the temperature and the thickness of the skin. When the body gets cold, the blood is brought back to the main organs, leading to extremities getting colder, due to the lower volume of blood in the vessels. With less the blood being pumped to the vessels, the PI is reduced. Hence, the closer the PPG is measured to the tip of the finger, the higher the risk of degradation of the PPG signal.

Calluses on the skin increase the distance between the vessels and the surface, lowering the PI. As they are most often located on tip of the fingers, distal phalanges are not recommended.

For these and general wearability reasons, the proximal phalanges are better PPG sensor location candidates.

The PPG signal should be measured on the palm side of the phalanges, and be robust against the rotational orientation of the device on the axis of the finger. The small finger diameter allows for the possibility of more complex sensing schemes among synchronised modules and different wavelengths to perform reflective and transmissive PPG.

Finger cross-section

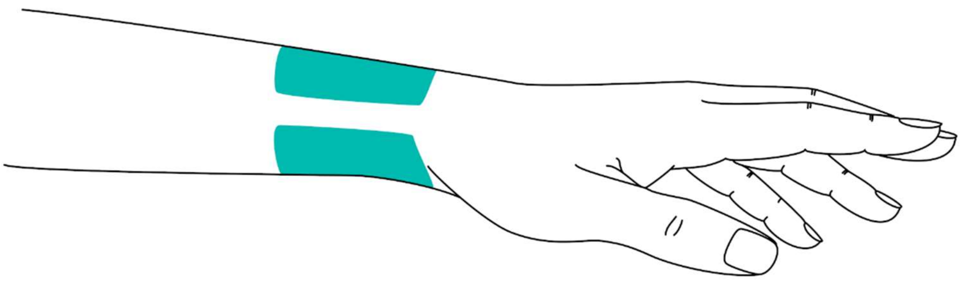


Each module can be configured to pulse light for itself or another sensor. The deeper penetration of the long wavelengths can be used for transmitted PPG.

Wrists

The wrist is widely used to monitor PPG, because of the habits of wearing a bracelet or a watch and because of the bigger volume available. While there are fewer risks of the type caused by cold skin or calluses than the finger, this location has three downsides:

- The surface can be covered with hair or tattoos, mainly on the upper part
- The arm is highly prone to movements and bracelets cannot be as tight as rings
- The proportionally larger tissue on the wrist with respect to the finger affects the PI, since more DC light is reflected with respect to the AC component. This results into lower SNR and higher power consumption.



Even though the upper part of the wrist isn't ideal in term of body location for PPG, it is yet usually chosen for its simplicity of design and its better perfusion compared to the bottom side. There are two types of design that are widely used:

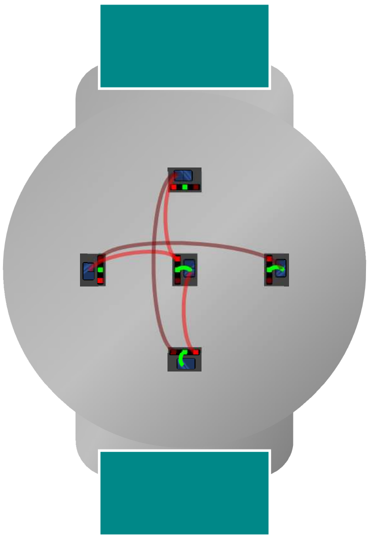
A single module centred on the dial

+ Low consumption
- The noise generated by the movements is difficult to filter
- Loss of contact due to movement or hairiness are frequent

Central LEDs surrounded by several photodetectors

+ More continuous and easily filterable signal
- High consumption of LEDs

Due to its extreme small size - multiple, synchronized SB140_M1 modules can be considered. In this case, power consumption is much lower than the "Central LED" design, while maintaining the advantage of signal continuity and quality. As in the case of the finger, the different modules can be used to emit the light and generate many different optical paths. This allows a spatial “scanning” of different wrist locations skin, making the PPG signal acquisition essentially custom-fit for a given user.



Summary of the PPG locations

Location	Vascularisation	Perturbations	Ease of integration	Number of recommended modules
Ears	+++	-	+	2
Fingers	++	--	++	3
Wrists	+	---	+++	5