

Enhanced Actigraphy

This white paper has been produced to provide a technical overview of the development of enhanced actigraphy features in the Garmin Health SDK. Part of this paper has been presented during the Garmin Health Research Webinar on July, 19th 2023 by Justin Baird, Technical Lead Software Engineer at Garmin Health. A link to the full recording can be found in the references of this paper.

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Summary

- **Legacy Zero Crossings and Energy support activity classification, but are complex and susceptible to noise**
- **Addition of a configurable deadband to Legacy Zero Crossings removes noise susceptibility**
- **Enhanced Actigraphy provides activity classification that is simple in calculation and highly configurable to different actigraphy use cases**

Introduction – Actigraphy and Garmin

An actigraph, a diminutive wearable device commonly positioned on the wrist, functions as a recording instrument that captures bodily activity through the detection of physical motion. Its principal application pertains to the evaluation of sleep duration and quality. Evidently, Garmin watches serve as exemplars of actigraphs providing metrics such as step counts, activity detection and sleep tracking, all of which are conveniently accessible through the Garmin Health Software Development Kit (SDK) [1].

However, it is imperative to recognize that these metrics are not comprehensive in addressing the full spectrum of potential actigraphy applications. In an

ideal scenario, researchers would have unrestricted access to complete accelerometer datasets, thereby enabling customized analytical procedures. In addition, practical limitations, including constrictions in data storage capacity and bandwidth, impose substantial constraints on such endeavors. For instance, a Garmin Vivosmart 5 device, as an illustrative example, possesses the capability to retain approximately one day's worth of uninterrupted raw acceleration data [2], necessitating approximately a two-hour interval for complete retrieval via Bluetooth connectivity.

While Garmin is actively engaged in augmenting both storage capacity and bandwidth capabilities, it is evident that long-term data logging remains an impractical proposition in numerous instances. This significant challenge is what drove the creation and development of enhanced actigraphy features as part of the Garmin Health SDK.

Legacy Actigraphy

Legacy actigraphy, known as “accelerometer sum of zero axis crossings” or “zero crossings” or just “ZCROSS” logs to metrics in configurable intervals of 30 seconds or longer. The first metric, zero crossings, counts the number of times that the signal crossed the zero, indicating a frequency of motion. The second metric, energy, takes the integral of acceleration in the interval, indicating magnitude of motion.

Legacy Actigraphy – Zero Crossings

Zero crossing calculation starts with three axis accelerometer data at 25 hertz. The magnitude of three axis accel is computed as the two norm and one G is subtracted to remove gravity. The magnitude is then high pass filtered with a 0.5 hertz cutoff frequency implemented by subtracting the two second average acceleration.

A zero crossing is counted when the filtered magnitude crosses zero; that is, when the sign changes.

- 3-axis acceleration @ 25Hz
- $a = \sqrt{x^2 + y^2 + z^2} - 1$
- $a' = a - avg_{2sec}(a)$

- 0.5Hz high-pass filter
- $zC_t = \begin{cases} 0, & \text{sign}(a'_t) == \text{sign}(a'_{t-1}) \\ 1, & \text{sign}(a'_t) \neq \text{sign}(a'_{t-1}) \end{cases}$
 - Sample zero crossing
- $zC_{window} = \sum_{t \in window} zC_t$
 - Window zero crossing

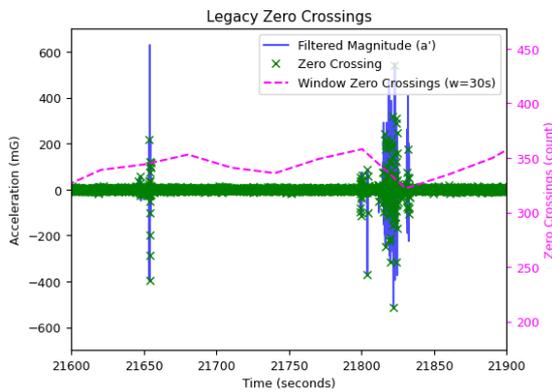


Figure 1, Legacy Zero Crossings

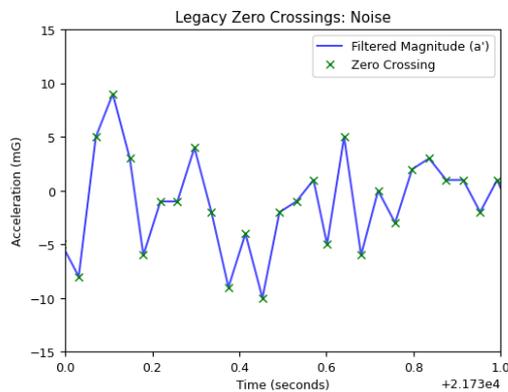


Figure 2, Legacy Zero Crossings: Noise

A major limitation of legacy zero crossings that can be seen in Figure 1 and Figure 2 is that accel noise causes zero crossings even when stationary. This causes zero crossings to be unintuitively higher when stationary than when in motion.

Legacy Actigraphy - Energy

The second metric, energy, is computed as the eight second root mean square of normalized acceleration updated every 2 seconds. Window energy is the sum of 2 second energy over the window.

- 3-axis acceleration @ 25Hz
- $a = \sqrt{x^2 + y^2 + z^2} - 1$
- $e_t = RMS_{8sec}(a_t)$
 - Sample energy
 - Note: Energy is updated every 2 seconds
- $e_{window} = \sum_{t \in window} e(t)$
 - Window energy

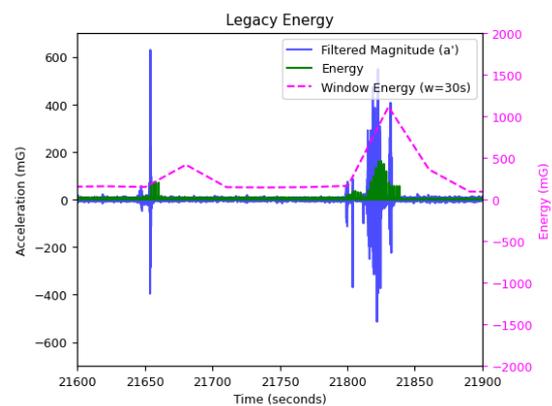


Figure 3, Legacy Energy

Legacy Actigraphy – Examples

Figure 4 below shows the legacy metrics for night of rather restless sleep, gathered using a Garmin Venu 2 Plus and the Health SDK. Zero crossings clearly show the noise issue: they float around 350 the whole night with little indication of motion. Energy appears to provide a good summary of motion.

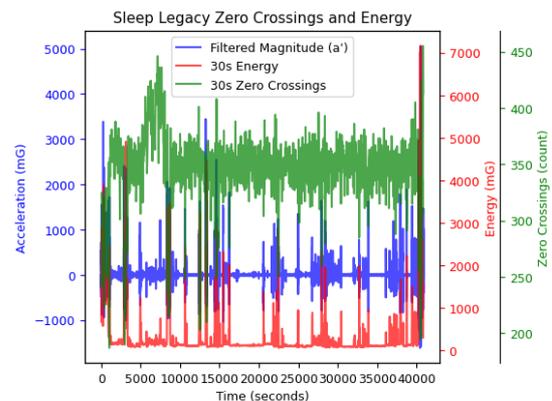


Figure 4, Sleep Legacy Zero Crossings and Energy

Figure 5 shows a walk dataset. The walk stands out clearly in energy and appears as a reduction in zero crossings. With the walking segment identified with the energy metric, zero crossings can then be used to determine the frequency of motion. 100 zero crossings in 30 seconds gives around a three step per second cadence.

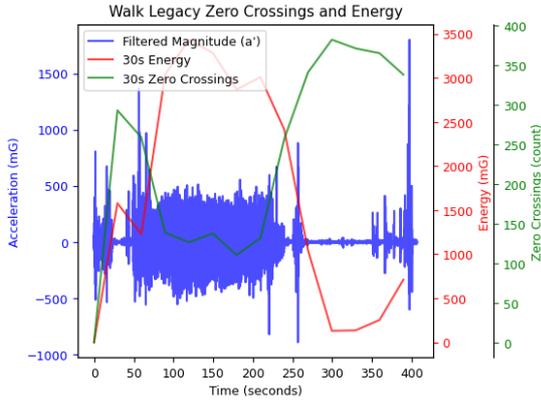


Figure 5, Walk Legacy Zero Crossings and Energy

Legacy Actigraphy Improvement - Deadband

In surveying actigraphy literature about zero crossings, we found that zero crossings are typically implemented as threshold crossings with the threshold set above the accel noise floor, acting as a dead band. The Health SDK has added such a configurable threshold parameter to legacy zero crossings. This new threshold will default to 50 milliG, which is a common noise floor in Garmin device sensors, and is applied as follows. For a zero crossing to be counted, the sign of the accel must change and the absolute value of the accel must exceed the threshold. Figure 6 shows how this improves zero crossing behavior and makes it behave much more intuitively to track motion.

- 3-axis acceleration @ 25Hz
- $a = \sqrt{x^2 + y^2 + z^2} - 1$
- $a' = a - avg_{2sec}(a)$
- $zc_t = \begin{cases} 0, & \text{sign}(a'_t) == \text{sign}(a'_{t-1}) \text{ or } |a'_t| < \theta \\ 1, & \text{sign}(a'_t) \neq \text{sign}(a'_{t-1}) \text{ and } |a'_t| \geq \theta \end{cases}$
 - $\theta = \text{threshold}$
 - Sample zero crossing

- $zc_{window} = \sum_{t \in window} zc_t$
- Window zero crossing

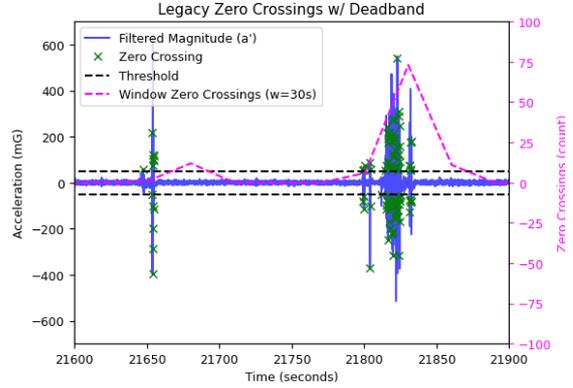


Figure 6, Legacy Zero Crossings w/ Deadband

Legacy Actigraphy Improvement Examples

Figure 7 shows the sleep data set again with a 50 milliG zero crossing dead band applied. Now, both zero crossings and energy have a high correlation with motion.

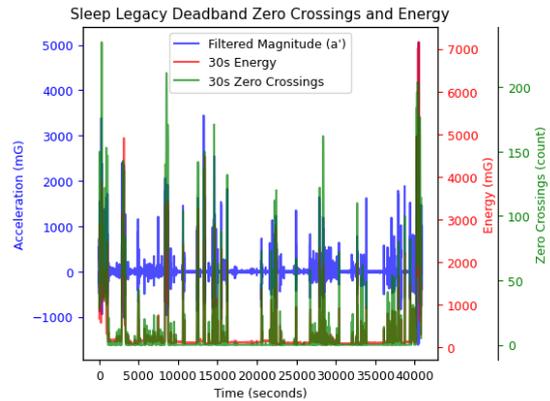


Figure 7, Sleep Legacy Deadband Zero Crossings and Energy

In the walk data set (Figure 8), the zero crossing value during the walk is unchanged, indicative of step rate, but now goes to zero with energy during the stationary section.

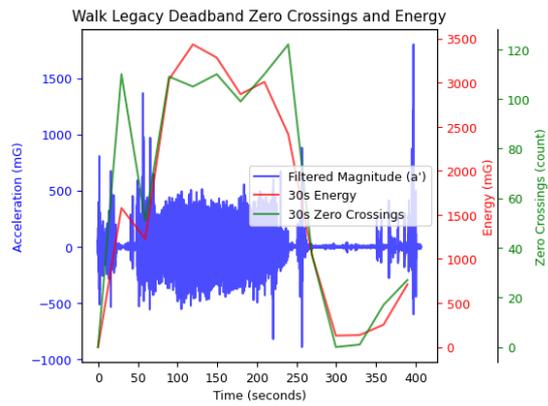


Figure 8, Walk Legacy Deadband Zero Crossings and Energy

This improvement goes a long way towards improving the usefulness of legacy zero crossings in the Health SDK, but legacy actigraphy still remains too rigid and too arbitrary to be useful for a large number of actigraphy use cases.

Enhanced Actigraphy

Introduction

Enhanced Actigraphy adds a new set of activity metrics to the Garmin Health SDK that address the limitations of Legacy Actigraphy. These new metrics are based on the analysis found in Maczák et al. [3].

The overall theme of the new metrics is configurability. They give researchers the ability to tune the metrics to their purposes rather than trying to find a one size fits all approach. To that end, the Health SDK is adding three new independently configurable actigraphy data sources. These sources have a shorter minimum processing window, down to one second, for higher granularity. They have also a set of configurable parameters which give two choices of filter path providing different acceleration behaviors, and an IIR filter with parameters for two second order sections to allow for custom high, low and band pass filtering. These parameters can easily be generated in SciPy or MATLAB. Finally, each source computes three metrics: zero crossings, energy, and time above threshold, each with independently configurable thresholds.

Enhanced Actigraphy Filter Paths

Enhanced Actigraphy calculation starts with 25 hertz three axes accel. For the first filter path, "FMPost", the magnitude is taken as the two-norm and the IIR filter is applied to produce filtered magnitude. In the plot a fourth order Butterworth high pass filter was used with a 0.25 hertz cutoff frequency. For the other filter path, "FMPre", the IIR filter is applied to each axis independently and the magnitude is taken as the two-norm of the filtered axes. The same fourth order filter was applied for this plot. As shown in Figure 9 and Figure 10, FMPre produces an absolute value magnitude rather than the signed magnitude of FMPost.

- 3-axis acceleration @ 25Hz
- Filter path: FMPOST
 - $a = \sqrt{x^2 + y^2 + z^2}$
 - $a' = f_1(f_0(a))$

- $f_i()$ = configuration-defined IIR filter

- Filter path: FMPre

- $f_i()$ = configuration-defined IIR filter

- $x' = f_1(f_0(x))$

- $y' = f_1(f_0(y))$

- $z' = f_1(f_0(z))$

- $a' = \sqrt{x'^2 + y'^2 + z'^2}$

$$\begin{aligned} x' &= f_1(f_0(x)) \quad y' = f_1(f_0(y)) \quad z' = f_1(f_0(z)) \\ &= f_1(f_0(z)) a' \\ &= \sqrt{x'^2 + y'^2 + z'^2} \end{aligned}$$

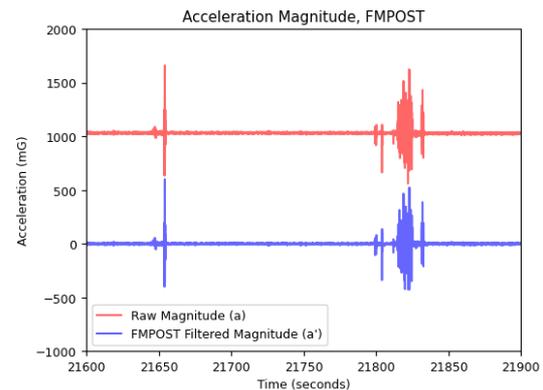


Figure 9, Acceleration Magnitude, FMPOST

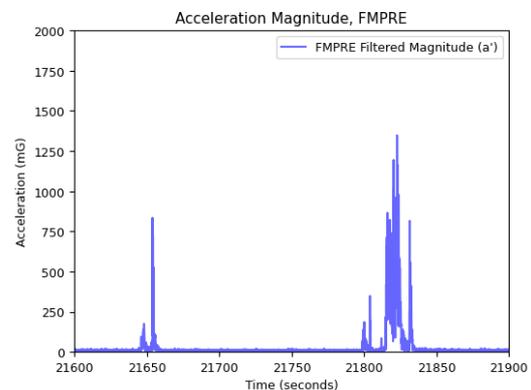


Figure 10, Acceleration Magnitude, FMPre

Enhanced Actigraphy Filter Path Comparison

Figure 12 shows the pros and cons of the different filter paths in dataset where the user is tapping the screen of their phone at 1-2 Hz. The individual taps are much more visible relative to noise in FMPre, but at the cost of loss of directionality information in the signal. The added sensitivity of FMPre will potentially be very useful for sleep studies.

- FMPre:
 - Increased sensitivity to small motion
 - Removes dominant gravity acceleration before 2-norm
- FMPOST:
 - Maintains directional information

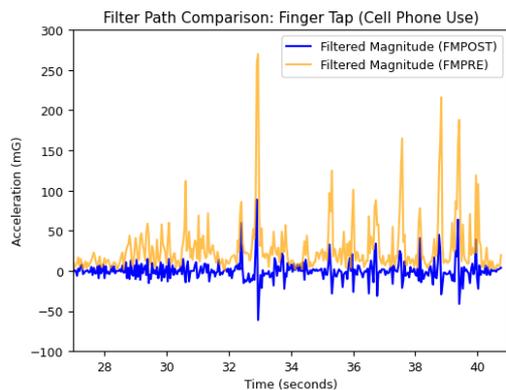


Figure 11, Filter Path Comparison: Finger Tap (Cell Phone Use)

Enhanced Actigraphy – Zero Crossings

In Enhanced Actigraphy, zero crossings are counted when the sign of the acceleration magnitude minus the threshold crosses zero. In the referenced article, it was shown that positive-only threshold produced comparable results to a positive and negative threshold band, so a positive-only threshold is used for simplicity. Note that the lack of directionality in the FMPre filter path produces a reduction in zero crossings during sustained motion as seen in Figure 14.

- 3-axis acceleration @ 25Hz
- Filter path: FMPre/FMPOST

- a' = filtered accel
- $zC_t = \begin{cases} 0, & \text{sign}(a'_t - \theta) == \text{sign}(a'_{t-1} - \theta) \\ 1, & \text{sign}(a'_t - \theta) \neq \text{sign}(a'_{t-1} - \theta) \end{cases}$
 - $\theta = \text{threshold}$
 - Sample zero crossing
- $zC_{\text{window}} = \sum_{t \in \text{window}} zC_t$
 - Window zero crossing

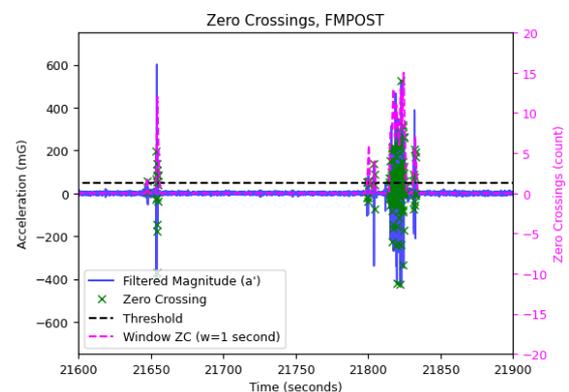


Figure 12, Enhanced Actigraphy Zero Crossings, FMPOST

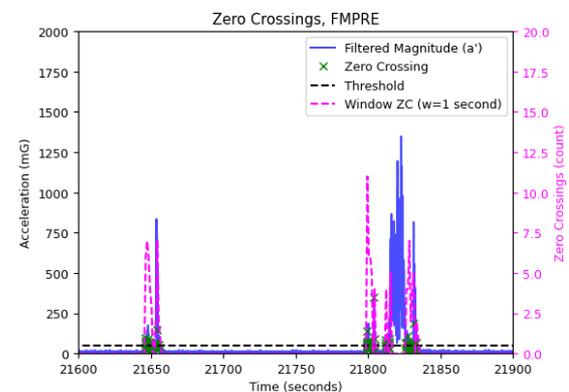


Figure 13, Enhanced Actigraphy Zero Crossings, FMPre

Enhanced Actigraphy – Energy

Sample energy is the absolute value of filtered magnitude, or zero if below the threshold. This simplifies energy greatly compared to the rolling window RMS of legacy energy. The FMPre energy looks similar but larger due to the absolute value magnitude.

- 3-axis acceleration @ 25Hz

- Filter path: FMPRE/FMPOST
 - $a' = \text{filtered accel}$
- $$e_t = \begin{cases} 0, & |a'_t| < \text{threshold} \\ |a'_t|, & |a'_t| \geq \text{threshold} \end{cases}$$
 - *Sample energy*
- $$e_{\text{window}} = \sum_{t \in \text{window}} e_t$$
 - *Window energy*

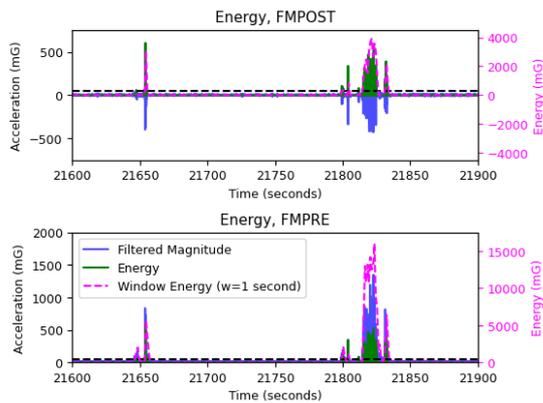


Figure 14, Enhanced Actigraphy Energy

Enhanced Actigraphy – Time Above Threshold

Time above threshold (TAT) is a new metric in Enhanced Actigraphy. Sample time above threshold is the sample period of 1/25 of a second when the sample is above the threshold and zero otherwise. For FMPre note that TAT values that are approximately doubled compared to FMPost due to the absolute value magnitude. Analysis of actigraphy data will need to be tuned to the filter path and scaling behavior, but this should be an acceptable tradeoff for the adaptability the filter paths will provide.

- 3-axis acceleration @ 25Hz
- Filter path: FMPRE/FMPOST
 - $a' = \text{filtered accel}$
- $$tat_t = \begin{cases} 0, & a'_t < \text{threshold} \\ 1/25, & a'_t \geq \text{threshold} \end{cases}$$
 - *Sample time above threshold*
- $$tat_{\text{window}} = \sum_{t \in \text{window}} tat_t$$
 - *Window time above threshold*

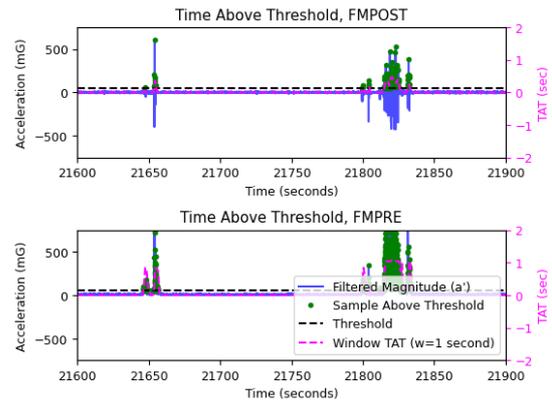


Figure 15, Enhanced Actigraphy Time Above Threshold

Enhanced Actigraphy Summary

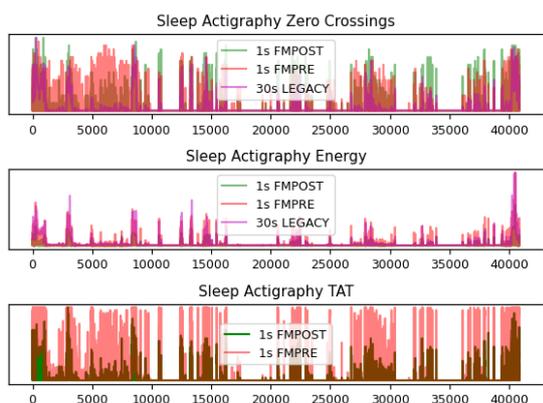


Figure 16, Sleep Actigraphy All Metrics

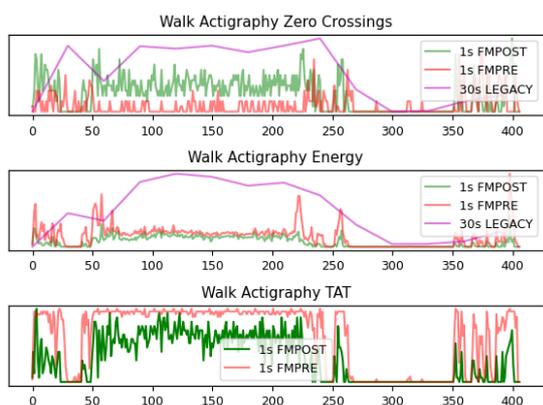


Figure 17, Walk Actigraphy All Metrics

Figure 17 shows the various metrics both legacy and enhanced actigraphy sources provide, plotted together on the sleep and walk data sets. New metrics are plotted with both filter paths and set to one second windows, but remember that the actigraphy in enhanced category can be set to any length of window in increments of one second. These settings provide a high level of variation in behavior for fine tuning.

For example, one actigraphy channel may be configured for high sensitivity, using the FMPRE filter path, a high-pass filter, and low thresholds to capture minute motions during sleep. At the same time, another channel may be configured to detect only large motions, using the FMPOST filter path, a band-pass filter, and high thresholds to capture only active behavior. The combination of these two metrics can provide a full picture of the users daily activity, at

down to a 1 second granularity, or in epochs as large as desired.

Conclusion

Figure 18 shows all of the activity metrics and configuration available on Garmin devices via the Garmin Health SDK as of the addition of Enhanced Actigraphy. Putting all of these knobs and switches in the hands of researchers will enable Garmin devices to be capable actigraphy platforms able to be tuned to fit many actigraphy use cases, or to match the behavior of reference actigraph devices.

Actigraphy Source	Activity Metric	Configuration
Legacy Zero Crossings		Interval (≥ 30 seconds)
	Zero Crossings	Deadband (mG)
Enhanced Actigraphy (3 channels)	Energy	Interval (≥ 1 second), Filter Path (FMPRE, FMPOST), IIR Filter Parameters (2 second order sections)
	Zero Crossings	Threshold (mG)
	Energy	Threshold (mG)
	Time Above Threshold	Threshold (mG)

Figure 18, Actigraphy Configuration Summary

Reference

- [1] <https://developer.garmin.com/health-sdk/overview/>
- [2] <https://www.garmin.com/de-DE/p/782585>
- [3] Maczák B, Vadai G, Dér A, Szendi I, Gingl Z (2021) Detailed analysis and comparison of different activity metrics. PLOS ONE 16(12): e0261718. <https://doi.org/10.1371/journal.pone.0261718>
- [4] [Webinar Recording](#)