Maxim Integrated PPG Algorithms Specifications

By Maxim Integrated Products, Inc.

Introduction

Maxim's health and wellness algorithms are available for customers who aim to create wearable devices with the state-of-the-art functions and with faster time to market. The Wearable Heart Rate Monitoring (WHRM) product includes heart rate (HR) and activity tracking algorithms, especially for the heart rate detection, cardiac beat detection, step measurement, and activity classification. The envisioned product targets health and wellness applications for continuous 24/7 monitoring with optimized power management and the provision of accurate heart rate (HR) and interbeat interval (IBI) detection, step detection, and sample-by-sample activity classification. The SpO₂ measurement algorithm provides oxygen saturation of the subject with the best-in-class accuracy. These algorithms are available with **MAX32664B/C** Biometric Sensor Hub to provide a complete embedded solution communication with Maxim's optical sensor products.

The respiration rate measurement (RRM) algorithm contributes with subject respiration rate which is another vital sign of the subject. Sleep quality assessment and sports coaching algorithms provide a general insight of the subject's wellness. These algorithms are available for various platforms by processing the outputs of **MAX32664B/C** Biometric Sensor Hub.

Maxim's WHRM Solution

Heart rate is the frequency of heart contractions that is measured in beats per minute (BPM). The pulse rate is the number of times the arteries create a measurable pulse due to the blood pressure change created by heart contractions. Normally, the photoplethysmographic (PPG) signal provides information about the pulse rate rather than the heart rate. However, we use "heart rate" which is a standard in the market.

Maxim WHRM algorithm utilizes synchronized 3-axis accelerometer and PPG data to provide several end-user-friendly fitness tracking outputs like heart rate and activity-related statistics, e.g., step count, burned calories, and activity class of a user. The PPG signal can be obtained from contractions of ventricles in finger, wrist, ear, toe, chest, etc.

Input Parameters

The Maxim HRM solution accepts additional user information of the subject as input parameters. These parameters include age, height, weight, and gender information that are accepted from a person.

These details are obtained at the initialization of the algorithm as shown in **Table 1**.

These input parameters (**Table 1**) are optional and default average values are used.

User Inputs	Notes
Age	The age of the person in years
Height	The height of the person in cm
Weight	The weight of the person in kg
Gender	The gender of the person

Table 1: *Maxim HRM Solution User Input Parameters*

Measurement Quality Metric

There are critical factors which affect the performance of PPG-based HRM like periodic/nonperiodic motion, electronic noise, mechanical/strap design, ambient light, melanin/skin color, low blood perfusion, etc.

Therefore, in order to report reliable heart rate, the quality of the measurement is the key factor. In validation phase, the report of the algorithm can be compared with an electrocardiogram (ECG)-based device and the quality/performance of the measurement can be calculated. However, in real-life conditions, there will not be a reference device to evaluate the quality of the measurement. Maxim's WHRM solution provides a measurement quality metric which enables evaluation of the heart rate reports sample by sample in real time.

Maxim's HR measurement quality metric scores the measurement between 0 and 100:

- **100%:** Perfect measurement quality
- **75%:** Good enough measurement quality
- **50%:** Mostly good enough measurement quality
- **25%:** Poor measurement quality
- **0%:** Unreliable measurement

Each heart rate value is reported with a measurement quality value in the algorithm so the heart rate report can be evaluated in real time. A sample of a challenging data set (**Table 2**) consists of a large number of data sequences with different activities like reclining, sitting, standing, sleeping, jogging, treadmill normal, fast, incline walking, treadmill/irregular walking, indoor/outdoor biking, running, elliptical machine, rowing, daily life, and overall (all activities/data points).

Rest (Reclining, Sitting, Standing, Sleeping)					
Data Points with Measurement Quality Metric	≥ 100	≥ 75	≥ 50	≥ 25	≥ 0
±5 BPM Accuracy [%]	98.77	98.28	97.75	97.42	97.34
Mean Absolute Error [BPM]	0.99	1.08	1.18	1.24	1.24
Reporting Coverage [%]	82.80	94.07	97.61	99.36	100.00
Walking					
Data Points with Measurement Quality Metric	≥ 100	≥ 75	≥ 50	≥ 25	≥ 0
±5 BPM Accuracy [%]	94.48	92.49	91.24	90.21	89.77
Mean Absolute Error [BPM]	1.67	1.86	1.98	2.18	2.26
Reporting Coverage [%]	64.04	84.07	93.34	97.99	100.00
Running					
Data Points with Measurement Quality Metric	≥ 100	≥ 75	≥ 50	≥ 25	≥ 0
±5 BPM Accuracy [%]	96.39	95.03	92.11	88.61	86.57
Mean Absolute Error [BPM]	1.36	1.67	2.07	2.63	3.04
Reporting Coverage [%]	55.12	72.79	82.46	91.15	100.00
Biking					
Data Points with Measurement Quality Metric	≥ 100	≥ 75	≥ 50	≥ 25	≥ 0
±5 BPM Accuracy [%]	95.81	94.22	92.27	90.41	89.71
Mean Absolute Error [BPM]	1.55	1.78	1.94	2.11	2.17
Reporting Coverage [%]	60.20	80.17	89.97	96.83	100.00
Overall					
Data Points with Measurement Quality Metric	≥ 100	≥ 75	≥ 50	≥ 25	≥ 0
±5 BPM Accuracy [%]	96.62	95.28	94.02	92.78	92.07
Mean Absolute Error [BPM]	1.34	1.53	1.68	1.88	1.99
Reporting Coverage [%]	67.13	84.45	92.16	96.94	100.00
>Daily LIFE					
Data Points with Measurement Quality Metric	≥ 100	≥ 75	≥ 50	≥ 25	≥ 0
±5 BPM Accuracy [%]	97.40	95.20	93.60	92.90	91.10
Mean Absolute Error [BPM]	1.34	1.41	1.47	1.61	1.82
Reporting Coverage [%]	53.00	75.00	88.00	96.00	100.00

Table 2: *Maxim HRM Solution Performance of the Measurement Quality Metric and Heart Rate Measurement*

± 5 Error Band Accuracy

It is the percentage of the valid data points which have absolute error of ≤ 5 BPM with respect to the reference device output (ECG chest strap). This metric is calculated in 1Hz.

Mean Absolute Error

Mean absolute error (MAE) is the average of the absolute difference of each Maxim HRM algorithm and the reference device output (ECG chest strap). This metric is calculated in 1Hz.

Reporting Coverage

It is the percentage of the valid data points which the measurement quality metric is greater than a certain threshold.v.

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Algorithm Outputs

Heart Rate

Maxim's HRM outputs showing the heart rate measurement with a quality metric have the properties as shown in **Table 3**.

Maxim's Heart Rate Monitoring

Parameter	Description
Measurement Unit	BPM - beats per minute
Update Frequency	1Hz
HR Report Range	30 BPM-210 BPM
Sensor Inputs	PPG and 3-axis Accelerometer
Activity Type	All (tested with lying down, sitting, standing, sleeping, jogging, walking, biking, elliptical machine, rowing, and daily life)
First Reporting Time	5s-15s
Input Parameters	See Input Parameters section
Outputs	Heart rate in BPM, measurement quality score between 0 and 100

Table 3: Maxim HRM Solution Specifications

Sampled Mode Heart Rate

The sampled mode heart rate consists of switching on the optical signal during short-time intervals and obtain an estimation of the heart rate as fast as possible. There are two key factors in the sampled mode heart rate measurement:

- evaluate when a short-time estimation is reliable (to turn off the light-emitting diodes [LEDs])
- obtain a reliable estimation with minimal information about the history of the measurement

The algorithm outputs are obtained when the short-time estimation is reliable with the help of the measurement quality metric. The heart rate is calculated between 5 seconds and 20 seconds based on the signal quality and activity type. The update rate of the heart rate report is controlled by the user in sampled mode and no measurement is applied between two sampled mode heart rate measurements, which enable power saving. See **Table 4**.

Maxim's Heart Rate Monitoring

Parameter	Description
Measurement Unit	BPM - beats per minute
Update Frequency	Configurable (e.g., 1 measurement per 1 minute, 1 measurement per 10 minutes, etc.)
HR Report Range	30 BPM - 210 BPM
Sensor Inputs	PPG and 3-axis accelerometer
Activity Type	All
First Reporting Time	5s-20s
Input Parameters	See the Input Parameters section
Outputs	Heart rate in BPM, measurement quality score between 0 and 100

Table 4: Maxim HRM Solution Sampled Mode Heart Rate Specifications

Interbeat Interval

The time interval between the individual heartbeats is called an interbeat interval. It is a crucial health indicator. It is the primary input for the heart rate variability that is used for heart health and autonomous nervous system health. It may also be used in a wide spectrum of applications, such as clinical practice, sleep quality measurement, and stress and recovery analysis.

Maxim's IBI accuracy in resting condition is as follows:

MAE 7ms, extra beat detection of 3%, missed beat of 2%, and with 95% of coverage See **Table**.

Parameter	Description
Measurement Unit	Milliseconds
Update Frequency	Every heartbeat
IBI Report Range	285ms–2000ms
Sensor Inputs	PPG and 3-axis accelerometer
Activity Type	Resting
First Reporting Time	5s–15s
Input Parameters	See Input Parameters section
Outputs	IBI in ms, Measurement Quality Score in discrete percentage: **0%** No output, **25%** Bad signal **50%** Moderate, **75%** Good **100%** Perfect

Signal Requirements

- Proper sensor to skin coupling should be satisfied. The watch should fit snugly and comfortably.

- Accelerometer and PPG signal sampling rate should be 25Hz, with sampling interval between 38ms and 43ms.

- Accelerometer to PPG synchronization should be within 25ms, with reference to the sample timestamps.

- There should be accelerometer and PPG data point drops for no more than one sample per minute.

Reference Device

- Heart Rate - Consider using an ECG chest strap with a minimum of 250Hz sampling rate, such as Polar H10.

Signal Quality Requirement

Maxim's algorithm expects the signal quality with peak signal-to-noise ratio (pSNR*) > 15dB at rest and 6dB during exercise on each of the green PPG channels to achieve the accuracy numbers shown in **Table 2**. The HR frequency is the dominant frequency in the PPG spectrogram.

Note: For pSNR calculation (also known as AC signal SNR), signal power is defined to be the power of the signal at the heartbeat frequency in addition to its second and third harmonics. The noise power is defined to be the power of all other signal components, including motion artifacts.

Activity Classifier

Maxim's activity type metric outputs the user activity state in continuous mode. The activity type metric is enhanced with machine learning-based algorithm with the large dataset of real data. The activity classifier is an independent module that does not require the PPG input to function. See **Table 6**.

Parameter	Description
Unit	Activity Type
Activity Types	▪ Rest ▪ Walk ▪ Run ▪ Bike
Sensor Inputs	3-axis Accelerometer
First Reporting Time	2s

Table 6: Maxim HRM Solution Activity Classifier

Table 7 shows an example for the performance of Maxim's activity classifier.

Activity Type	Accuracy [%]	Recall	Precision
Rest	99	0.93	1.00
Walk - Indoor	96	0.97	0.91
Run - Indoor	98	0.93	0.96
Walk - Outdoor	95	0.95	0.99
Bike - Outdoor	98	0.85	0.95

Table 7: Maxim HRM Solution Activity Classifier Performance

Energy Expenditure

Maxim's energy expenditure (EE) metric outputs the energy expenditure depending on the activity type of that moment in time. Maxim HRM algorithm is able to output both passive EE (basal metabolic rate - BMR), active EE (active metabolic rate - AMR) and total EE that corresponds to a sum of passive and active EE rates in metabolic equivalent of task (MET - kcal/kg/h) metric. See **Table 8**.

Parameter	Maxim HRM EE
Definition	Accumulated EE since the last reset of algorithm
Measurement Unit	kcal
Sensor Inputs	3-axis Accelerometer
Input Parameters	Age, Gender, Height, Weight, Activity
Output	▪ BMR ▪ AMR ▪ Total EE

Table 8: Maxim HRM Solution Energy Expenditure

Step Counts

Maxim's step counting feature outputs the total step counts based on the wrist motion for both walking and running considered to be separate activities. See **Table 9**.

Parameter	Maxim Step Count
Measurement Unit	Number of Steps
Sensor Inputs	3-axis Accelerometer
Output	▪ Total Walking Steps ▪ Total Running Steps

Table 9: Maxim HRM Solution Step Counts

Table 10 shows an example for the performance of Maxim's step counting feature.

Activity Type	Absolute Percent Error of Step Counts (%)
Walk - Indoor	0.90
Run - Indoor	4.18
Walk - Outdoor	6.45

Table 10: *Maxim HRM Solution Step Counting Feature Performance*

Cadence

The cadence is expressed as the number of steps per minute that is detected in rhythmic activities such as walking, running, and biking. See **Table 11**.

Parameter	Maxim Cadence
Measurement Unit	Steps/minute
Sensor Inputs	3-axis Accelerometer
Suitable Activity	Walking, Running, Biking
Update Frequency	25Hz
Output	Cadence

Table 11: *Maxim HRM Solution CadencePerformance*

SpO2 - Blood Oxygen Saturation

The SpO2, also known as blood oxygen saturation, is a measure of the amount of oxy-hemoglobin relative to the total amount of hemoglobin in the arterial blood. The SpO2 level is reported in terms of percentage. It has been considered as one of the five vital signs indicating the status of the body's life-sustaining functions in addition to the heart rate, respiratory rate, blood pressure, and body temperature. Maxim's SpO2 measurement solution functions as a drop-in module for wrist-worn health bands as well as finger-based pulse oximetry devices. The specifications of SpO2 algorithm are summarized in **Table 12**.

Parameter	SpO2
Measurement Unit	Percentage (%)
Input Sampling Frequency	25Hz
Update Frequency	1Hz
Range	70%-100%
Accuracy (RMSE)	3.5%
Sensor Inputs	PPG, 3-axis accelerometer
Suitable Activity	Rest, Sleep
First Reporting Time	~20s
Output	SpO2, signal quality flags, motion flag

Table 12: *Maxim SpO2 Algorithm Specifications*

Maxim SpO2 Algorithm Requirements

The necessary operating conditions for SpO2 algorithm are as follows:

- The sensor to skin coupling should be proper.
- The wearable device should fit snugly and comfortably.
- The user should place the wearable device on the wrist gently without a need for extra pressing to obtain the signal. No over- or under-pressing should be done.
- Subjects should not squeeze their arms, hold anything during measurement, or wear other devices on the same wrist.
- Subjects should be free of deformities or abnormalities or other health issues that can prevent proper use of the device under test.
- Subjects shall be free of known heart arrhythmias such as atrial fibrillation, atrial flutter, paroxysmal supraventricular tachycardia (PSVT), ventricular tachycardia, ventricular fibrillation, premature atrial contraction, bradyarrhythmia, premature ventricular contractions (PVCs), long QT syndrome, sinus node dysfunction and heart block.
- Accelerometer-to-PPG data acquisition synchronization should be within 25ms, with reference to the sample timestamps.
- The sensor to skin coupling should be proper.

The minimum signal quality requirements for SpO₂ algorithm are as follows:

- Perfusion index range
  - ◊ $PI \geq 0.2\%$
- Sampling rate
  - ◊ Red/IR PPG 25Hz
- Signal continuity
  - ◊ Greater than 30s of continuous RED/IR PPG signal with 'Low PI', 'Low SNR,' and 'Motion' flags set off
- Signal-to-noise ratio
  - ◊ PPG signal quality with AC SNR > 35dB (time domain) and pSNR > 10dB (frequency domain) at rest where
    - AC SNR is defined as: SNR = 20 * Log (PAC / PNoise) where PAC is "peak-to-peak amplitude of PPG pulse" and PNoise is "RMS of AFE noise."
    - For pSNR calculation, the signal power is defined to be the power of the signal at heartbeat frequency in addition to its second and third harmonics. The noise power is defined to be the power of all other signal components, including motion artifacts.

Respiration Rate

The respiration rate is a vital sign indicating the health and wellness and can be an input for several applications, such as sleep quality assessment, stress level estimation, and energy exposure estimation, etc. Maxim RRM algorithm is a wearable solution to measure the user's respiration rate by the PPG signal gathered from the wrist or fingertip. See **Table 13**.

Parameter	Respiration Rate
Measurement Unit	1 breath per minute (brpm)
Input Sampling Frequency	25 samples per second
Update Frequency	25Hz
Range	6brpm-30brpm
Accuracy (MAE)	1.6brpm (At rest)
Sensor Inputs	PPG
Suitable Activity	Rest, Sleep
Latency	~60s
Output	Respiration rate, Output confidence level (0%–100%)

Table 13: Maxim Respiration Rate Algorithm Specifications

Sleep Quality Assessment

Sleep is restoration process of the body; efficiency of the restoration is directly correlated to the amount of time spent at each sleep phase. Absence of any of the sleep phases or lack in the durations of the sleep phases can cause severe diseases and problems with cognitive skills. Hence, tracking of the sleep phases is vital for human beings. Maxim sleep quality assessment (SQA) algorithm delivers automatic tracking of sleep through the wearable devices. See **Table 14**.

Parameter	Sleep Wake State	Sleep Wake State
Measurement Unit	Sleep State	Sleep Phases
Input Sampling Frequency	1 sample per second	
Update Frequency	Every 30s	Every 5min
Range	Sleep/Wake	Light/Deep/Rapid Eye Movement
Accuracy	92%	66%
Input Parameters	Heart Rate, IBI, Accelerometer Magnitude, Activity	Heart Rate, Interbeat Interval, Accelerometer Magnitude, Activity
Suitable Activity	Rest, Sleep	Sleep
First Reporting Time	Up to 5min	Up to 30min
Latency	Up to 30min	
Configuration Parameters	Age, Gender, Weight, Resting Heart Rate	
Output	Sleep/Wake State, Latency Report, Update Flag	Sleep Phase, Update Flag

Table 14: Maxim Sleep Quality Assessment Algorithms Sleep/Wake and Sleep Phase Detection Specifications

Sports Coaching

To achieve a healthy life, sports need to be a part of the individuals' lives. People need to plan and keep a track of their sports performance and the frequency to adjust their lifestyle so that they can keep themselves healthy. With the widespread use of wearable devices, people have started to use them for keeping a track of their vital signs (heart rate, SpO_2 level, etc.) and sports activities (walking, running, biking, etc.). As the next step, wearable devices need to serve people to track their sports activities.

VO_2 MAX is the maximum rate of oxygen consumption that a user can reach during an exercise. The VO_2 MAX of a subject is an indicator of the subject's fitness level.

The fitness age is a metric that interprets the subject's VO_2 MAX score in terms of the human age. See **Table 15**..

EPOC is the amount of oxygen required to restore the subject's body to its homeostasis. Homeostasis is the state of the living body where it is steady both physically and chemically. Therefore, EPOC is an indicator of the training effect on the user's body. See **Table 15**.

Parameter	VO₂ MAX	Excess Post-Exercise Oxygen Consumption (EPOC)
Measurement Unit	1ml/min/kg	1ml/kg
Input Sampling Frequency	25 samples per second	
Update Frequency	1 output per session	
Range	0-100	0-200
Sensor Inputs	PPG	
Suitable Activity	Rest (Relax)	Rest (After Exercise)
First Reporting Time	Up to 6min	Up to 5min
Input Parameters	Age, Gender, Weight, Height	Age, Gender, Weight, Height, Exercise intensity, Exercise duration, Elapsed time after exercise
Output	VO₂ MAX, Fitness Age	EPOC, Recovery Time

Table 15: *Maxim VO₂ Max Measurement and EPOC Measurement Algorithm Specifications*

The recovery time is the time required for the human body to reach homeostasis. During recovery time, the body repairs and prepares for the next training which is necessary to increase the sports performance in a healthy way. See **Table 16**.

Readiness Score is an HRV-based metric. It represents the physical state of the body and measures how ready is the body for the next training. See **Table 16**.

Parameter	Recovery Time	Readiness Score
Measurement Unit	Minutes	No units
Input Sampling Frequency	25 samples per second	
Update Frequency	1 output per session	
Range	0-∞	1-100
Sensor Inputs	PPG	
Suitable Activity	Rest (After Exercise)	Rest
First Reporting Time	Up to 5min	
Input Parameters	Age, Gender, Weight, Height	
Output	Recovery Time	Readiness Score

Table 16: *Maxim Recovery Time Estimation Algorithm and Readiness Score Algorithm Specifications*

Heart Rate Variability

The heart rate variability (HRV) is a very important indicator of a person's health. Maxim HRV algorithm uses IBI information to generate various HRV metrics. These metrics are especially crucial for sports coaching and stress assessment. Please see **Table 17** for algorithm specifications.

Parameter	HRV
Measurement Unit	ms for time domain metrics ms² for frequency domain metrics
Inputs	Beat-to-beat duration in ms along with timestamp information *(Remark: The algorithm can handle missing IBI values up to 20%, and occasional extra ones, which occur at most once in 10 seconds.)*
Input Range	300ms–2000ms
Outputs	Time domain metrics: AVNN, SDNN, RMSSD, pNN50 Frequency domain metrics: ULF, VLF, LF, HF. LF/HF, TOTPWR
Output Update Rate	Configurable: 1 second to 6 minutes Default value: 30 seconds
Latency	HRV is a window-based calculation. Window size is configurable: 25s–360s. Default Value: 300s
Suitable Activity	Rest, Sleep

Table 17: *Maxim Heart Rate Variability Algorithm Specifications*

Automatic Exposure Control

The Automatic exposure control (AEC) algorithm is responsible for optimizing Maxim's PPG sensor analog front-end settings for optimum power consumption and heart rate measurement performance. Please see Table 18 for the algorithm specifications.

Parameter	AEC
Inputs	PPG and Accelerometer Data
Input Frequency	25Hz
Outputs	Analog front-end settings: • LED Current • Integration Time • Sample Averaging Setting
Output Update Rate	25Hz
Latency	None
Suitable Activity	Rest for smart target level computation, all other activities for matching the LED level to the target

Table 18: *Maxim Automatic Exposure Control Algorithm Specifications*

Stress Monitoring

Daily life stress is one of the important issues of modern life. Mainly, two kinds of stress phenomena exist as acute and chronic stress. Acute stress arises because of pressure from the recent past and near future. For example, exercise challenges or any kind of sudden anxiety can induce acute stress. On the other hand, chronic stress results from the long-term pressures like socioeconomic conditions, ongoing problems in relations, etc. Maxim Stress Monitoring algorithm provides a quick stress assessment for acute stress of the subjects using wearable devices.

Parameter	Stress Score
Measurement Unit	No units
Input Sampling Frequency	25 samples per second
Update Frequency	1 output per session
Range	0-18
Suitable Activity	Rest
Input Parameters	Time domain HRV metrics (AVNN, SDNN, RMSSD, pNN50) Freq domain HRV metrics (ULF, VLF, LF, HF, TOTPWR)
Output	Stress score (See **Table 19**), stress class, stress percentage

Stress Score	Description
0-8	Represent stressful scores from highest to lowest levels where sympathetic system is dominant
9-18	Represent nonstressful scores from highest to lowest levels where parasympathetic system is dominant

Table 19: *Interpretation of Stress Score*