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“Coping with motion artifacts by analog front-end ECG microchips under variable digital resolution and gain”

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CONTENTS

PROBLEM STATEMENT

- ✓ A trend in mHealth devices is that ECG wearables capture events that occur infrequently, when the user performs daily activities that likely include movement.

- ✓ Portable ECG devices are fabricated with resolutions below 16 bits, typically of 12 bits, which might be sufficient for the purpose of monitoring. But when high gain is applied to observe waveform details, motion artifacts can easily saturate the system.

- ✓ Some heart operation details, such as "late potentials" or some cardiomyopathies, require very high-resolution, greater than 20 bits to show up the small potential amplitudes [1].

- ✓ This represents a challenge for developers who, in addition to designing noise removal filters, must consider motion artifacts that can interfere with ECG recordings.

JUSTIFICATION

A resolution greater than 18 bits with low gain is required to:

- Identify very low amplitude ECG potentials.
- Maintain a detailed ECG signal with low gain.
- Improve motion artifact's control.
- Provides a more suitable signal for post-processing and machine-learning data mining.

BACKGOUND

- Electrodes on the wrists and ankles create a long space for other muscles to introduce EMG noise, which cannot be removed as a common mode noise.
- Long cables are required to reach the electrodes, and dangling cables cause changes in the baseline.
- Some works propose for the resolution of motion artifacts the use of accelerometer and intelligent algorithm for their reduction.
- Our methodology is based on a previous work [3] for rapid prototyping of ECG device, using the AFE AD8232 and Bluetooth communication, but now centered on solving the motion artifacts problem using variable resolution and gain.

PROJECT OBJECTIVES

General Objetive:

- The objective of this paper was to identify and propose a solution for coping with motion artifacts in the ECG signal using a standard configuration in the AFE stage, but with variation of gain and ADC resolution in a portable ECG system.

HARDWARE- CONNECTIVITY

Prototypes connectivity

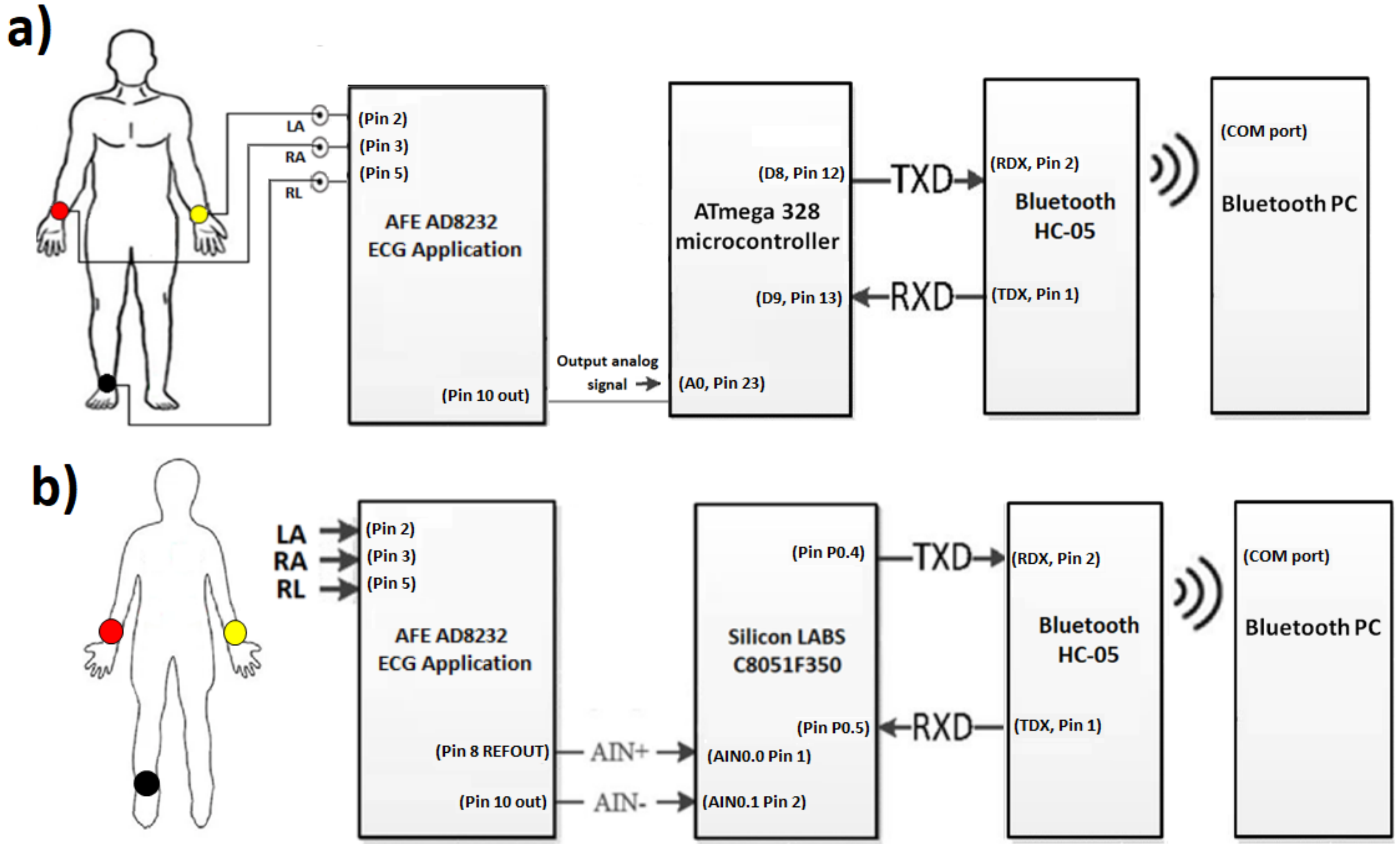

Figure 1. a) Low-resolution ECG system diagram with Arduino platform (ATmega328).
b) High-resolution system diagram for ECG monitoring with Silicon LABS platform (C8051F350)

MATERIALS AND METHODS

TEST SUBJECTS AND TEST

For this methodology and experimentation, ECG signals of two human volunteers were captured:

1) **Volunteer A:**

- Healthy male
- Height:1.71m
- Age: 27 years
- Weight:105Kg
- Electrical axis of the heart: 3 degrees
- Recorded lead DI
- IN+ corresponding right arm (RA)
- IN- corresponding left arm (LA)
- Reference corresponding right leg (RL)

2) **Volunteer B:**

- Healthy male
- Height:1.77m
- Age: 23 years
- Weight:61Kg
- Electrical axis of the heart: 120 degrees
- Recorded lead DII
- IN+ corresponding right arm (RA)
- IN- corresponding right leg (RL)
- Reference corresponding left arm (LA).

In this work, tests on resting state, stationary gait, and on a treadmill at different speeds were made on the human volunteers described, to investigate the problem and determine an effective way to cope with motion artifacts.

AFE STAGE AD8232 SIMULATION OF ECG CONFIGURATION

At this stage, simulation of the cardiac monitor configuration was obtained from two simulation software tools available with ECG configuration from AD8232 datasheet bandwidth:0.5-40Hz and gain of 1100x.

- NI multisim (figure 3b)
- AD8232 filter design software (Figure 3c)

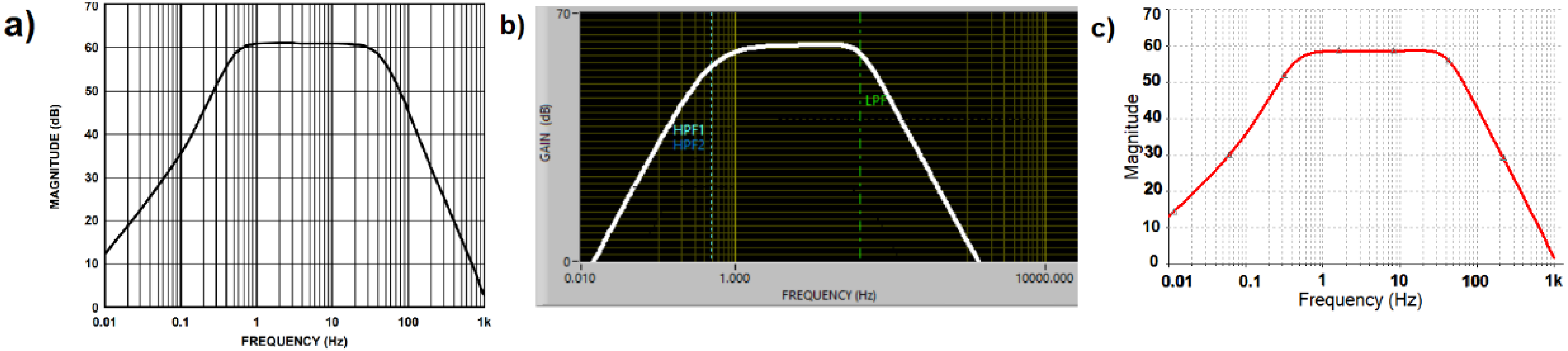

Figure 2. Cardiac Monitor configuration frequency response a) Frequency response indicated on datasheet. b) Frequency response indicated by Filter Design software. c) Frequency response simulated on NI multisim software.

LOW- AND HIGH-RESOLUTION MICROCONTROLLER CHARACTERIZATION

The ECG configuration with variable gain was evaluated under two microcontroller systems of different ADC resolution:

- Arduino Nano ATmega328 (Low-resolution system)
- Silicon LABS (C8051F350) (High-resolution system)

Platform microcontroller	Arduino Nano ATmega328	Silicon LABS (C8051F350)
Maximum sampling frequency.	15000 SPS	1000 SPS
ADC resolution	10 bits	24 bits
ADC type)	Successive approximation	Sigma-delta with on-chip calibration
Analog input type	Single-ended	differential
Digital memory)	32 Kbytes of Flash and 2KB of RAM	8 Kbytes of Flash and 768 bytes of RAM

Table 1. Low and High resolution microcontroller systems: Arduino Nano (ATmega328) and Silicon LABS (C8051F350) platform characterization.

RESOLUTION, SAMPLE RATE AND GAIN SETTINGS

In the high-resolution Silicon Labs platform, a software routine to characterize the development board was executed. Capturing 128 samples of the 24-bit ADC, for a noise measurement, connecting AIN0 and AIN1 to AGND at the terminal block of the board. The standard deviation (σ) of a sample set is equivalent to the effective RMS noise of the conversion system.

OWR (Hz)	RMS noise (digital units)	SNR (dB)	Effective bits
10	10.87	117.78	19.63
60	28.06	109.51	18.25
120	64.54	102.45	17.08
180	149.52	94.97	15.83
360	851.06	79.87	13.31
500	1882.77	72.98	12.16
1000	9527.46	58.89	9.82

Table 2. Noise, SNR, and Resolution at different sample rates using the Silicon Lab C8051F350 microcontroller.

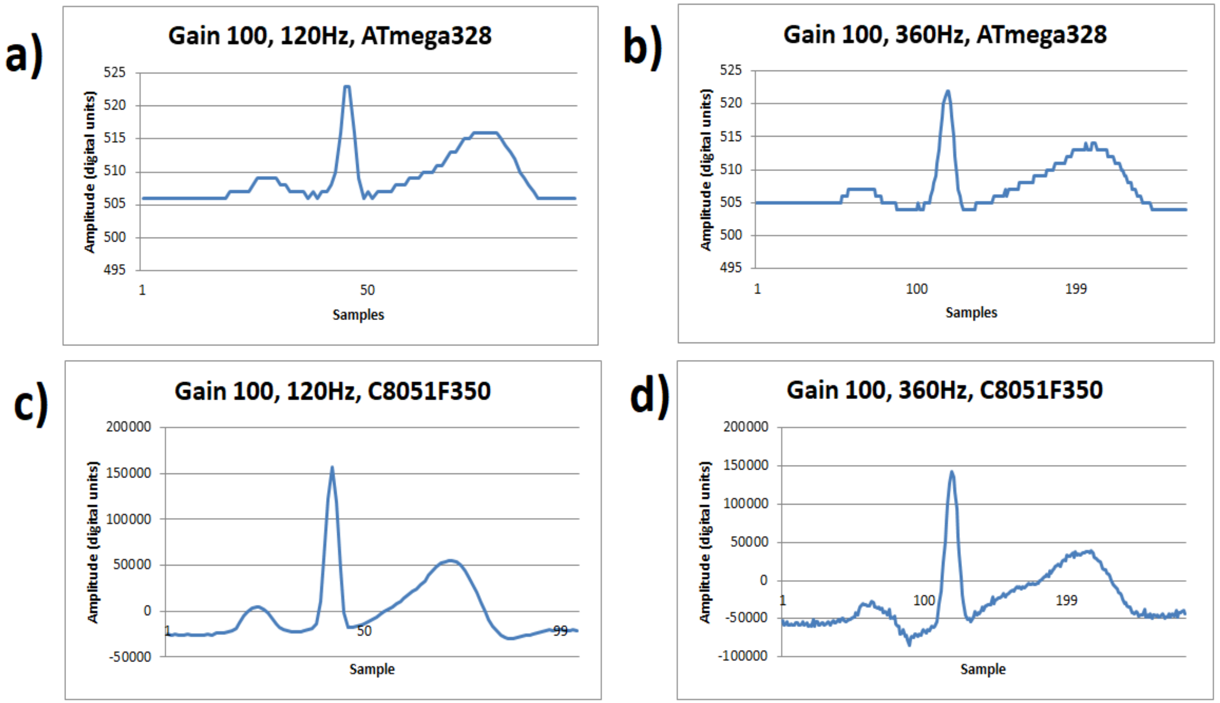

Figure 3. ECG signal from human volunteer A, (lead I). a) Gain 100x, sample rate 120Hz on ATmega328 microcontroller, b) Gain 100x, sample rate 360Hz on ATmega328 microcontroller, c) Gain 100x, sample rate 120Hz on C8051F350 microcontroller, d) Gain 100x, sample rate 360Hz on C8051F350 microcontroller.

ECG SIGNAL ADQUISITION

- After defining the filtering stage, the sparkfun board and breadboard cardiac monitor configuration in the AFE stage were implemented. Using the Arduino Nano and silicon LABS platforms; bluetooth transmission with the HC-05 module in board on board mode was incorporated.

- The software to receive and display the signal was the Arduino integrated development environment (IDE) with its add-ons, Serial Monitor, COM ports, and Serial Plotter.

- The bluetooth module and COM ports were configured at a baud rate of 115200 and the sample rate for both microcontroller platforms was set to 180Hz.

- Signals were obtained for high-resolution and low-resolution microcontroller, with 100x and 1100x gain.

ECG prototypes low and high-resolution.

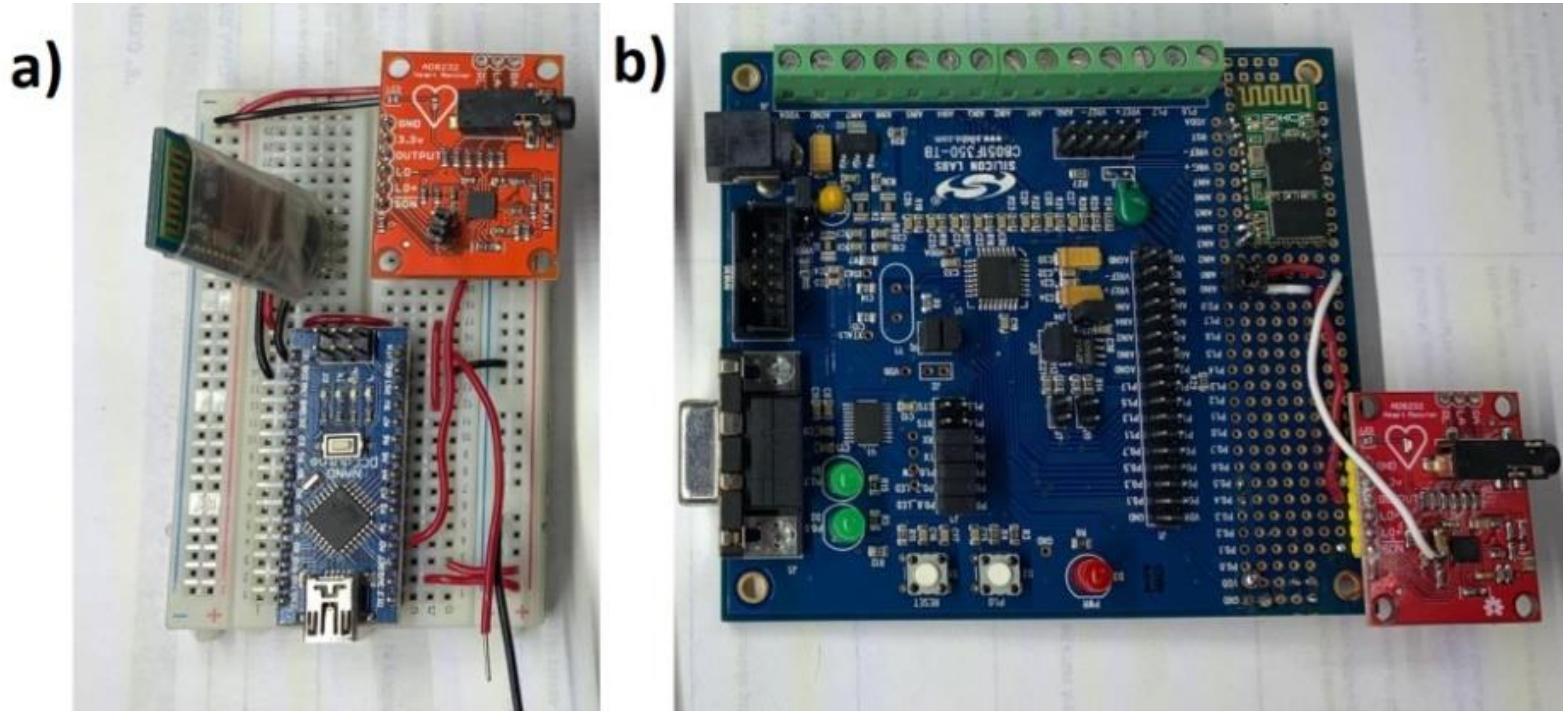

Figure 4. a) Low-resolution ECG system with Arduino platform (ATmega328).
b) High-resolution system for ECG monitoring with Silicon LABS platform (C8051F350).

In both cases, the Sparkfun AD8232 module with minor modifications was used for the analog stage.

RESULTS

ECG Signals:

The ECG signals shown in figure 5 were captured on resting conditions, sample with rate of 180Hz, for two different gains of the microcontroller systems.

ECG amplitude signal range:

a) 19 digital units

b) 268 digital units

c) 208,030 digital units

d) 4,135,239 digital units

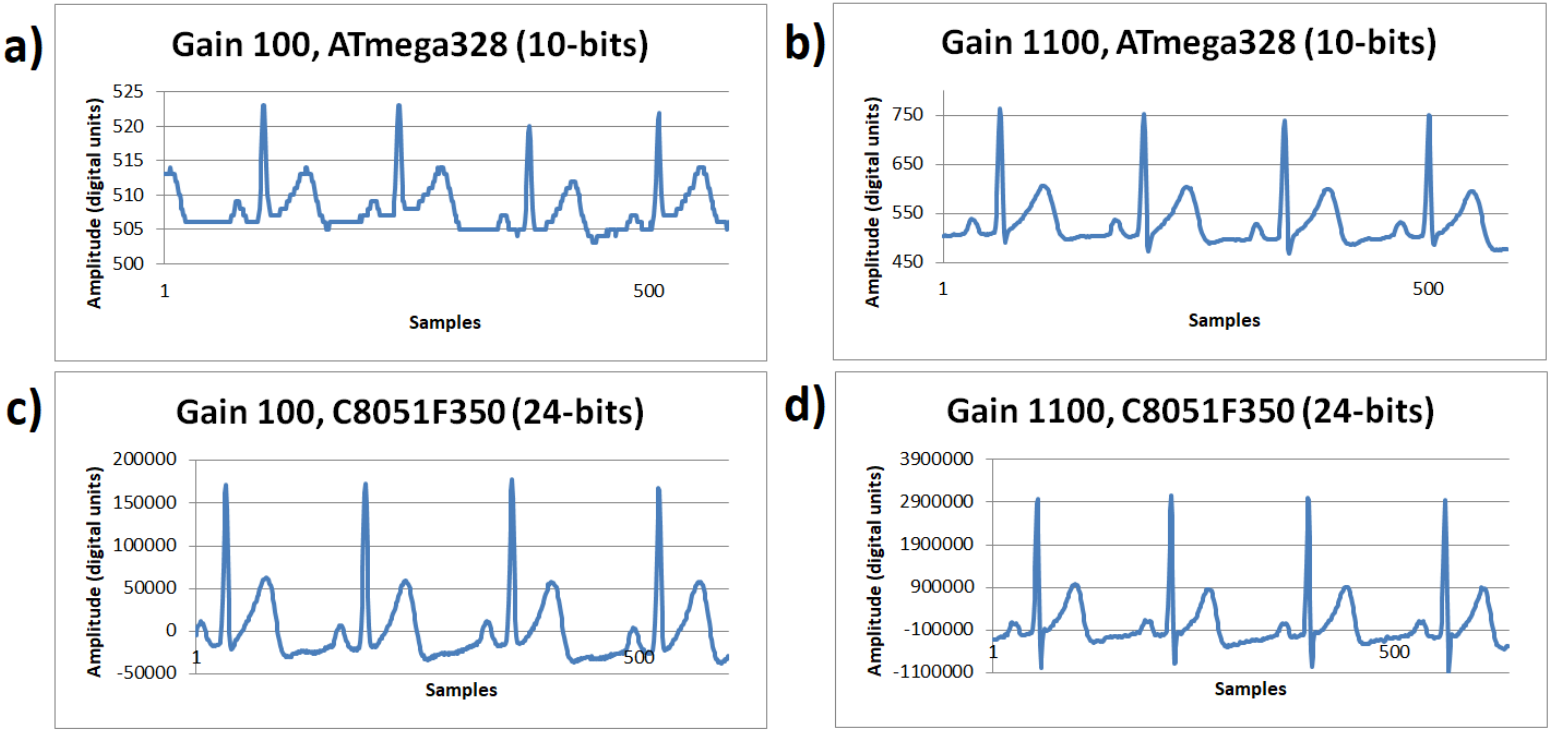

Figure 5. ECG signals sampled at 180Hz rate from human volunteer A on resting state (lead I). a) Gain 100x, ATmega328 (10-bits) with 100x gain. b) ATmega328 (10-bits) with 1100x gain. c) C8051F350 (24-bits) with 100x gain. d) C8051F350 (24-bits) with 1100x gain.

System saturation:

Non resting tests were implemented to investigate how the motion artifacts works to reach system saturation. Human volunteer B did a stationary gait with fast sudden movement. This consisted on the volunteer walking slowly without moving from their place, during approximately four seconds, and then suddenly moving their arms to produce a motion artifact. On figure 6 the low-resolution (10 bits) system was used.

- Figure 6 a) shows the system with 1100x gain on which red lines correspond to the lower and upper saturation limits of 0 and 1023 respectively.
- Figure 6 b) shows ECG signal obtained with 100x gain, this signal looks small because the same axis scale as in figure 6 a) is being used to compare. It is observed that a higher margin is present to prevent system saturation.
- Figure 6 c) corresponds to the same signal as in figure 6 b) but scaled out to observe the details of the signal, the ECG signal did not supply enough information, however, system saturation due to motion artifacts is solved.

System saturation:

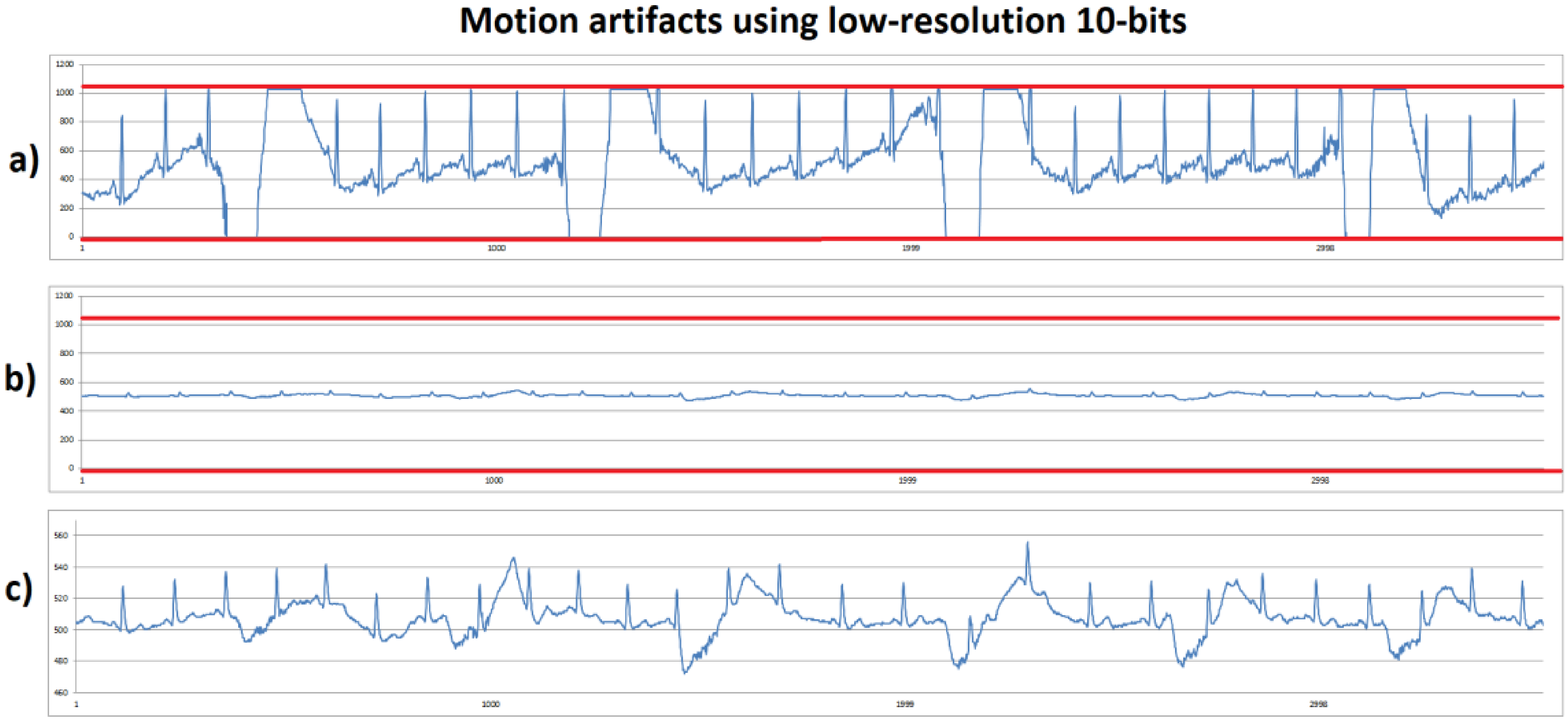

Figure 6. ECG signals from human volunteer B (lead DII) at stationary gait with a fast sudden movement using low-resolution 10-bits platform. a) Motion artifact causing saturation limits reaching (red lines) using 1100x gain. b) Motion artifact without saturation using 100x gain with scale 0-1023. c) Motion artifact without saturation using 100x, without adjusted scale.

RESULTS

System saturation:

The same stationary gait with a fast sudden movement test was executed by human volunteer B using the high-resolution (24 bits) system with 100x and 1100x gain.

- Figure 7 a) shows the system with 1100x gain that during motion artifact reaches saturation at the lower and upper limits with an amplitude of ±5,339,000 digital units (red lines); this saturation lines correspond to the minimum and maximum output of the AFE converted to the 24-bit ADC levels.
- Figure 7 b) shows the system with 100x gain and a vertical axis scale from ±6'000'000.
- Figure 7 c) shows the same signal as in figure 7 b) but with a lower vertical axis scale.

RESULTS

System saturation:

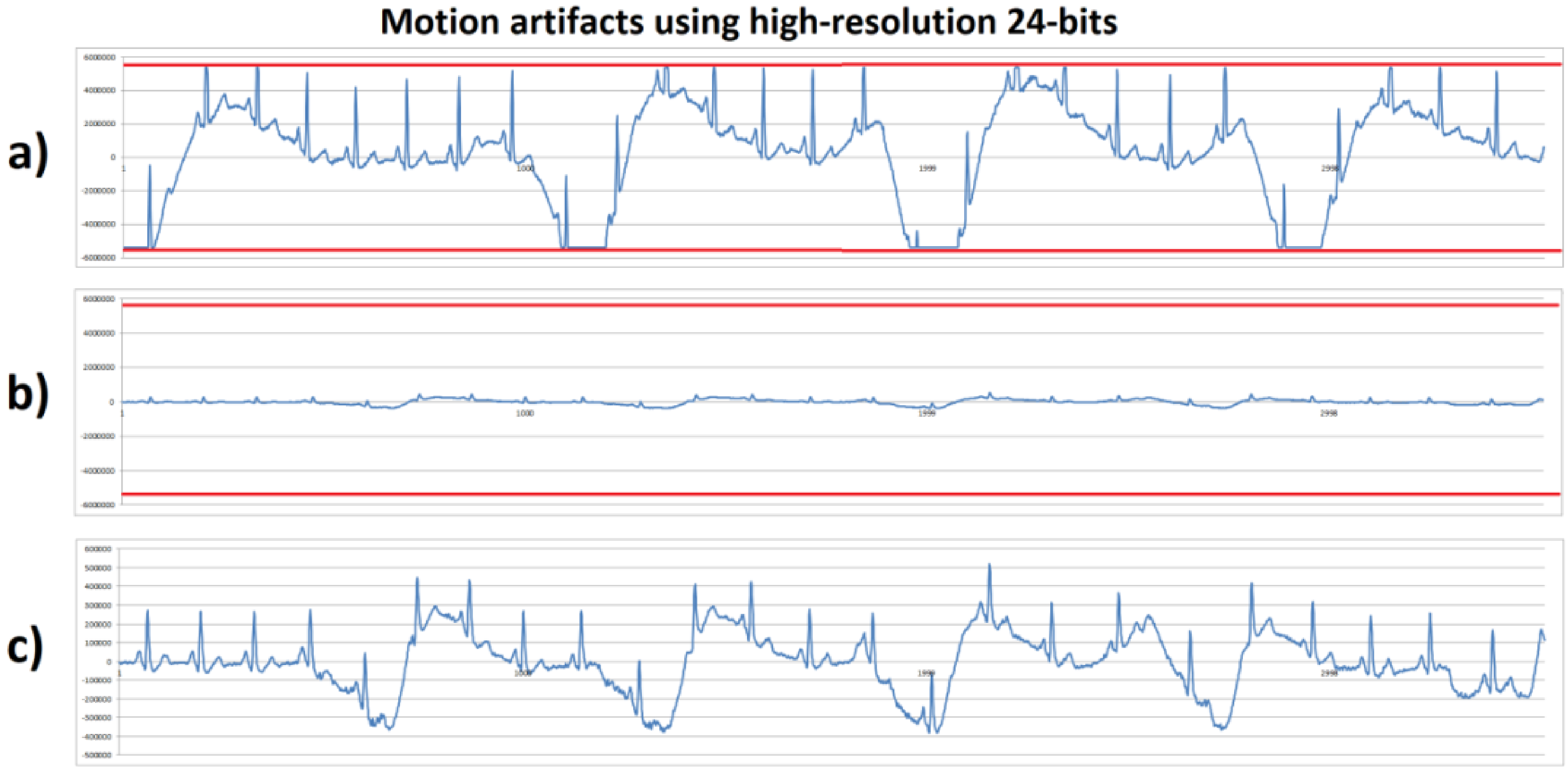

Figure 7. ECG signals from human volunteer B (lead DII) at stationary gait with a fast sudden movement using high-resolution 24-bits platform. a) Motion artifact causing saturation limits reaching (red lines) using 1100x gain. b) Motion artifact without saturation using 100x gain with scale ±6,000,000. c) Motion artifact without saturation using 100x gain, without adjusted scale.

ECG Signals:

Finally, post-processing tests using MATLAB's Filter Designer application were made to reduce motion artifacts. Signals were first analyzed applying a fast Fourier transform to identify possible motion artifact frequencies. Subsequently, a second order butter-worth filter was used to attenuate the motion artifact frequencies of about 1Hz and below, the motion artifact was considerably reduced.

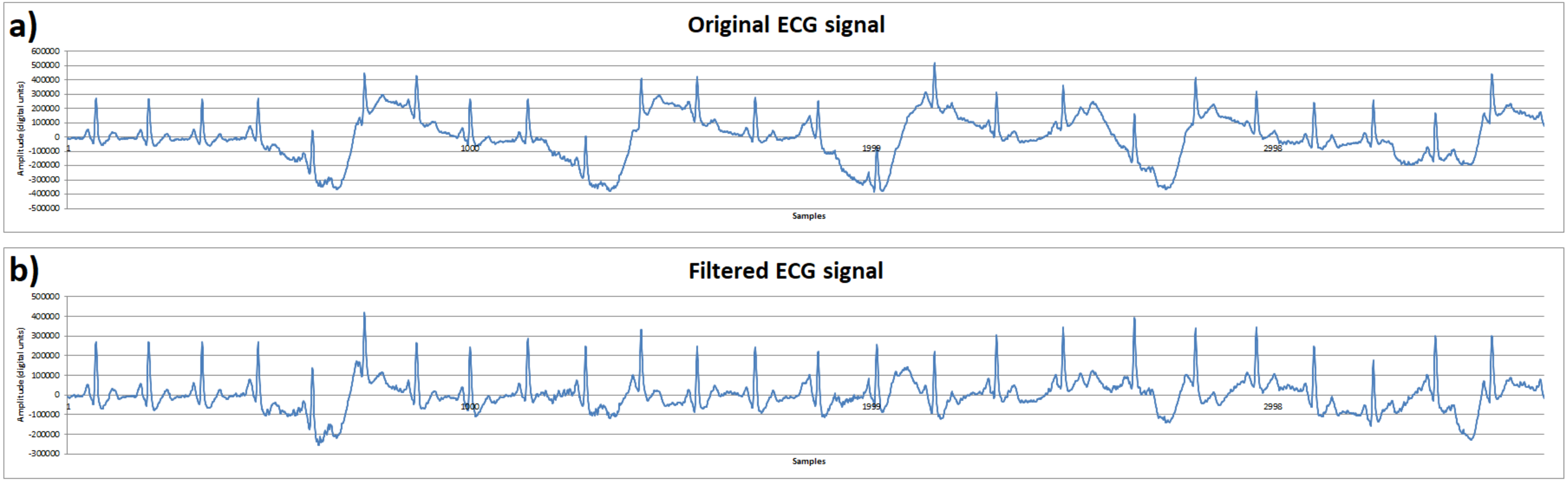

Figure 8. ECG signal from human volunteer B (lead DII). a) Original signal. b) Filtered ECG signal with a second order Butterworth filter to reduce motion artifacts.

RESULTS

The signal was not saturated using the treadmill at different speeds with a gain of 100.

Low-resolution (10-bits) Arduino | **High-resolution (24-bits) SiliconLABS**

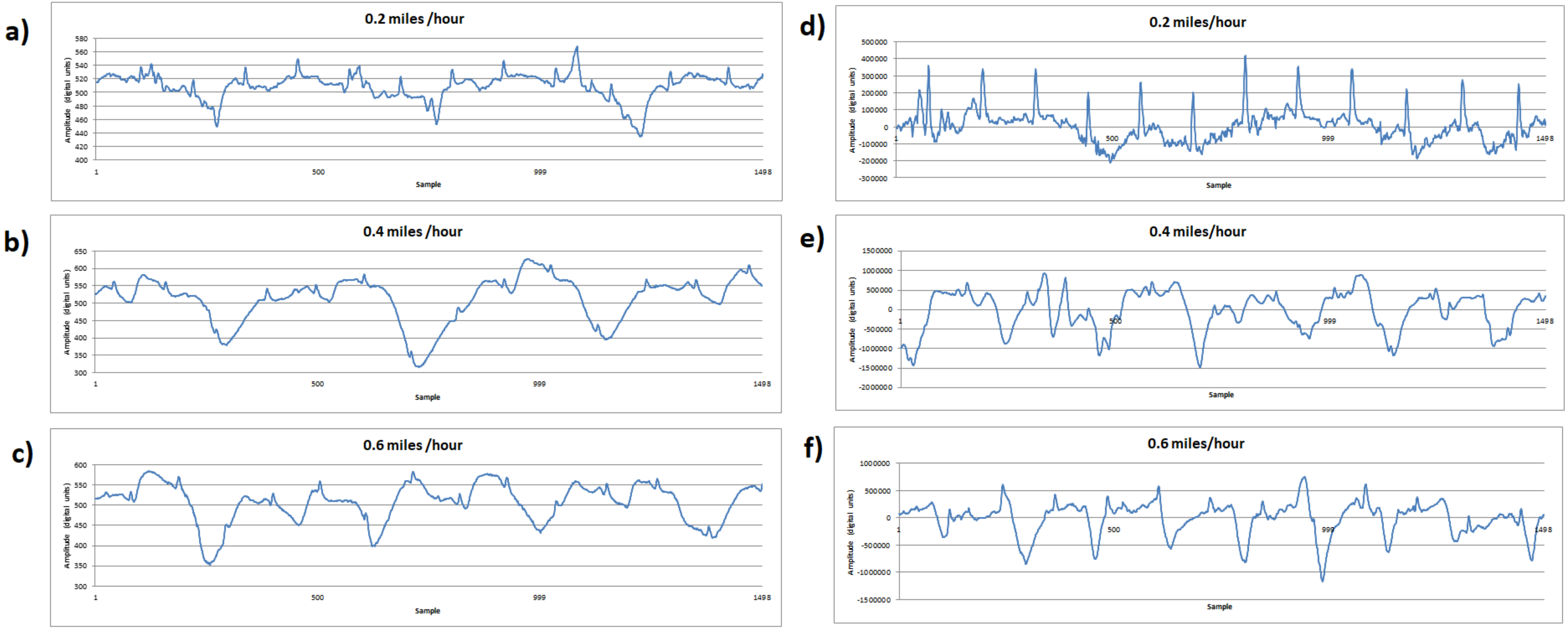

Figure 9. ECG signals using the treadmill at different speeds. a) 10-bits at 0.2 miles/hour, b) 10-bits at 0.4 miles/hour, c) 10-bits at 0.6 miles/hour, d) 24-bits at 0.2 miles/hour, e) 24-bits at 0.4 miles/hour, f) 24-bits at 0.6 miles/hour.

CONCLUSIONS

- The low-resolution (10-bits) Arduino platform, exhibited a large quantification error in resting conditions that hides the presence of input noise introduced by both the electrode-skin contact and the amplifier electronics, at any sampling rate.

- The high-resolution (24-bits) silicon labs platform showed a higher susceptibility to RMS input noise as sampling rate increases (see table 2 and figure 4).

- It was observed that on resting state, the arduino platform solves the ECG signal's waveform properly, but after motion tests this system shows sensibility to saturation due to motion artifacts when using 1100x gain. When lowering the system's gain to 100x, saturation problem is solved but low resolution does not supply a detailed ECG signal.

- Silicon Labs platform with 1100x gain shows a detailed signal, but sensitive to saturation due to motion artifacts. However, this problem is solved by lowering the system's gain to 100x, which prevents the system to reach saturation due to motion artifacts and shows a detailed ECG signal.

CONCLUSIONS

- The gain of the analog signal chain must be low to accommodate voltage fluctuations without saturation of the A/D converter. A gain of 587x was calculated as the highest possible without producing saturation. Also, a high number of bits (24 bits) of the A/D converter can be used with a low gain to maintain signal detail.

- Other tests on a treadmill at different gait speeds and a gain of 100x were made, but the ECG signal was significantly distorted without saturating. Low gain and higher ADC resolution help reduce the effect of the motion artifacts, but in addition to analog cutoff frequencies and classical post-processing, the usage of other hardware designs and advanced software post-processing is necessary to entirely solve the motion artifact problem, in order to recover the single ECG signal from the acquired noisy signal.