Power-Line Interference Removal from High Sampled ECG Signals Using Modified Version of the Subtraction Procedure

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Research

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Abstract

Background

The acquired ECG signals are often contaminated by residual Power-Line Interference (PLI). A lot of methods, algorithms and techniques for PLI reduction have been published over the last few decades. The so called subtraction procedure is known to eliminate almost totally the interference without affecting the signal spectrum. The goal of our research was to develop a heuristic version of the procedure intended for ECG signals with high SR up to 128 kHz.

Results

The PLI is extracted from the corrupted signal by technique similar to second order band-pass filter but with practically zero phase error. The sample number as well as the left and right parts outside the samples belonging to a current sine wave are counted and measured. They are used to compensate the error arising with the shift between the moving averaged free of PLI signal samples and their real position along the linear segments (usually PQ and TP intervals having frequency band near to zero). The here calculated PLI components are appropriately interpolated to 'clean' the dynamically changed in amplitude and position contaminated samples within the non-linear segments (QRS complexes and high T waves).

Conclusions

The reported version of the subtraction procedure is tested with 5 and 128 kHz sampled ECG signals. The maximum absolute error is about 20 μV except for the edges of the recordings. Finally, an approach to PLI elimination from paced ECG signals is proposed. It includes pace pulse elimination, signal re-sampling down to 4 kHz and subtraction procedure implementation followed by adding back the pace pulses.

Keywords: power-line interference, subtraction procedure, high sampled ECG signals, paced ECG signals

Background

The acquired ECG signals are often contaminated by residual Power-Line Interference (PLI) that cannot be sufficiently suppressed despite the usually high common mode rejection ratio of the contemporary instrumentation amplifiers. This is due to the leakage currents flowing through the patient cable, the unequal electrode impedances and the body [1]. As a result, the PLI is transferred into false differential signal superimposing the heart activity voltage by sinusoidal noise with main frequency of 50 or 60 Hz, possibly accompanied by 3rd and 5th harmonics. DC component and even harmonics are missing as the power generators are made with precision half-wave symmetry. Generally, the PLI amplitude and frequency are variable. The amplitude changes derive from the spurious electrical circuits. The frequency deviation of the power supply is limited by the standards within ±0.5 Hz. The fluctuations are slow but each difference toward the rated frequency must be canceled immediately once the algorithm is started and currently compensated both for short clinical records and Holter monitoring.

Enormous number of methods, algorithms and techniques for power-line interference reduction has been published over the last few decades. Recently some cancellation techniques were proposed, other were again discussed: traditional and sophisticated notch filters, adaptive and Kalman filtering, Savitzky-Golay smoothing filter, Fast Fourier (FFT) and Discrete Wavelet Transforms (DWT), Recurrent Neural Networks (RNN), modified time-domain subtraction and regression subtraction methods [2, 3, 4, 5, 6, 7, 8].

The traditional notch filters affect the ECG spectrum usually defined from 0.3 through 125 Hz. Filter with narrow bandwidth results in lower signal distortions but cannot get through higher PLI frequency deviations. Kher [7] modified a second-order FIR filter introducing pair of complex-conjugated poles to obtain a more selective bandwidth. However, the only figure presented shows reduced amplitudes of several high and steep R waves.

Avendaño-Valencia *et al*. [4] proposed a tracking method based on Kalman filtering with parameters optimized through genetic algorithms. A clean ECG signal is superimposed by PLI with constant, as well as with variable amplitude and frequency. It is then subjected to the proposed filtration. The results show higher performance compared to the estimation–subtraction method and the non-linear adaptive estimator of non-stationary sinusoids. In fact, a quantitative assessment cannot be made as the differences between the original and the processed signals are not presented.

A trained model based on RNN is used to adapt the amplitude and the phase of a 50Hz sinusoid to the current PLI waveform [6]. The modified interference is then subtracted from the ECG signal. The results obtained show a 10.5% improved Signal-to-Noise Ratio (SNR). Bhoi1 *et al*. [8] published a comparative analysis of several filtering techniques applied to 60 Hz PLI suppression in ECG signals. The statistical evaluation is based on SNR, Mean Square Error (MSE), Root MSE, Peak SNR and peak to peak amplitude. The results suggest that the noise cancellation performance obtained by DWT is better compared to the other techniques. Actually, the ECG analysis is known to be time-amplitude. ECG waves are delineated; the amplitudes, widths, intervals and relationships between them are measured and compared to statistically created sets of data to classify the revealed morphology as normal or pathological heart activity. That is why SNR, MSE and similar measures are not the adequate metrics for PLI suppression assessment.

Ch. Yu *et al*. [3] developed an improved adaptive coherent model approach, which is able to follow even fast interference changes at the reference input. The algorithm tracks the actual PLI frequency using partial FFT and then adjusts the sampling frequency of the ECG signal at the primary input. The authors illustrate the method by one recording only. They don't discuss the error committed.

The so called subtraction procedure has been developed some decades ago [9, 10]. It was further improved over the years [11, 12, 13, 14, 15, 16] and implemented in thousands ECG instruments and computer-aided systems [17, 18]. The subtraction procedure eliminates almost totally the interference without affecting the signal spectrum. Briefly, it consists of the following steps: (i) comb filter with first zero at 50 Hz is applied on linear segments (usually PQ and TP intervals having frequency band near to zero); (ii) the obtained free of interference values are used to compute phase locked interference patterns, saved in a set of corrections; (iii) they are subtracted from the corresponding samples of the corrupted ECG signal in the adjacent non-linear segments (QRS complexes and high T waves).

The subtraction procedure have been tested carefully by comparing conditionally clean ECG signals with processed contaminated signals, which are obtained by mixing the clean signals with synthesized interference. The difference observed is usually in the limits of ±20 μV, but the real error committed is lower since in fact the conditionally clean signals contain inherent noise. The results obtained do not depend on whether the synthesized interference consists of main frequency only or is mixed by its 3rd and 5th harmonics.

The procedure is extremely efficient even with changing PLI amplitude and frequency. The amplitude variations are taken in consideration by more frequent updates of the correction set using a less restrictive criterion for linear segment detection.

The frequency fluctuations are more difficult to overcome. The early solutions of the problem included small adjustments of the inter-sample intervals around their rated value [11]. According to an initial approach, each first sample of the PLI period is coupled to a given PL voltage level using Schmidt trigger connected to a secondary winding, the other samples being equally spaced at the rated inter-sample intervals. The irregular distance between this sample and the n^{th} sample of the previous PLI period results in small additional error, cancelled later on by an improved version: the length of each current period is measured and used for an equal sample allocation during the next period. However, the hardware tracking of the PLI frequency is not available both in battery supplied devices and computer-aided ECG systems, where additionally the analogue-to-digital convertor cannot be ongoing controlled.

A software approach dealing with the PLI frequency deviations was reported by Dotsinsky and Stoyanov [14]. The contaminated signal is band-pass filtered with cut-offs at 48 and 52 Hz. The cross point CP of the interference with the zero line is determined using homogenous triangles defined by the samples located below and above the zero. The CP position on the inter-sample interval is used to calculate the ongoing PLI fluctuation. The contaminated signal is re-sampled to turn the variable interference frequency into the rated one. Then, the PLI is removed. The processed signal is back re-sampling, thus restoring the original timescale.

The PL frequency variation is a special case of the non-multiplicity between the frequency and the sampling rate (SR) theoretically leading to not integer number of samples within a rated PL period. As an example, some AHA [19] database recordings, which are digitized with SR=250 Hz contain PLI frequency F = 60 Hz. The problem was overcome generalizing the structure of the subtraction procedure [12, 15]. Three modules are introduced: linear segment detection, PLI extraction and PLI temporal buffer. The basic manipulations are formulated as filters. The linearity is evaluated by the so called D-filter. A K-filter with zero in F and unity gain in 0 Hz removes the PL interference in the linear segments. A set of corrections is obtained by subtracting the filtered samples from the corresponding corrupted samples. The procedure is denoted as (1-K)-filter. The corrections are currently stored in the FIFO temporal buffer to be used in the following non-linear segments. A third B-filter with linear phase response and unity gain in F is introduced specifically for non-multiplicity cases. It extrapolates the stored FIFO values before being used to compensate the amplitude errors introduced by the appeared phase differences.

It is known that a 250 Hz SR would be acceptable for traditional ECG analysis [19]. However, some applications need higher SR. Bazhyna et *al*. [2] tested the efficiency of PLI suppression methods applied to high resolution ECG recordings with 1 kHz SR and 100 nV/bit resolution. When pacemaker's pulses have to be detected, an over 5 kHz SR is required. It may reach 16 to 128 kHz [21]. In such cases the ratio SR/F becomes 320 through 2560 for F = 250 Hz that slows down the implementation of the subtraction procedure. To cope with the problem, Mihov [16] developed appropriate changes in the procedure main stages. The efficiency achieved is manifested by ECG recordings with SR = 16 kHz.

Aim of the study

The purpose of this research was to create a heuristic version of the subtracted procedure intended for ECG signals with SR up to 128 kHz

Material

Recordings taken from the AHA database and re-sampled with 5 kHz, as well as paced ECG signals available in the database *PacedECGdb* [21] were mixed by synthesized interferences with 0.5 µV and 1 mV amplitude, respectively and variable frequency with rate of 1 Hz/10 s. The mixed signals are used to develop and test the algorithm and the program written in MATLAB environment. The chosen interference parameters exceed significantly the common values in practice but in this way the potential of the subtraction procedure can be better assessed.

Brief description of the algorithm

Preprocessing

The corrupted ECG recording (mixed signal) is processed by 1[st] order band-pass filter with central frequency at 50 Hz and cut-offs at 48 and 52 Hz. The appeared phase shift is compensated applying once more the filter backwards that corresponds to a second order band-pass filtered signal (BP signal) with practically zero phase error.

Linear segments

The used linearity criterion applied over two consecutive periods of F is

$$D = \mathrm{abs}\{[mix(k+N) - mix(k)] - [mix(k+2.N) - mix(k+N)]\} < M,$$

where k is the current sample of the mixed signal *mix*, N is the rated number of samples within the period, while M stands for the threshold defined as 100 µV.

Some problems arise with the determination of the free of interference values. Very often, the sample number inside the PLI period is variable. At the same time, the number of the inter-sample distances is usually not integer since the parts outside the samples belonging to a current BP sinusoid differ from the other distances. Besides, the calculated central mean value may do not coincide with any sample position. These problems were overcome as follows.

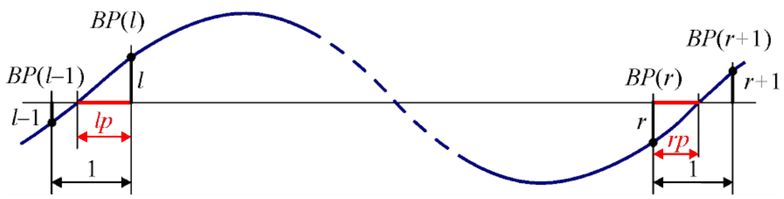

Fig. 1

The border left *lp* and right *rp* parts are investigated and computed (Fig. 1):

$$lp = \frac{BP(l)}{BP(l) + \mathrm{abs}\left[BP(l-1)\right]}; \quad rp = \frac{BP(r)}{BP(r+1) + \mathrm{abs}\left[BP(r)\right]}$$

Here l and r are current BP positions defining $BP(l)$ and $BP(r)$ as the leftmost and rightmost BP samples, respectively. The inter-sample distances are equated to one, the total outside part is $p = lp + rp$, the sample number N inside the wave is equal to $r - l$.

The mean total part $p_m = (p_i + p_{i+1})/2$ of two adjacent sinusoids i and $i + 1$ is used to average their corresponding *mix* intervals in sequence. The filtered samples *FS* from the last half of the first interval through the first half of the second one, are calculated dividing the consecutive sums of N mix samples S_N by $N-1+p_m$ instead of N. Thus, the error caused by not integer number of inter-sample distances will be compensated. Since the filtered samples $FS = S_N/(N-1+p_m)$ are coupled with the middle of the averaged intervals *mid*, they are additionally shifted to match real sample positions *sp* using the expression

$$FS_c(i) = FS(i-1) + [FS(i) - FS(i-1)]shift,$$

where $shift = sp - mid$ is the difference between *sp* and the middle of the averaged interval *mid*, determined as $mid = (N/2) + 0.5$ in case of integer inter-sample number and $mid = (N+p_m)/2$ otherwise.

The corresponding corrections are $C(i) = mix(i) - FS_c(i)$.

Further on, the two adjacent sinusoids in question are moved forward by one and subjected to the same processing till the end of the linear segment, the set of corrections being each time updated.

Non-linear segments

If the linearity criterion is not satisfied, the PLI elimination restarts with the already calculated corrections coupled with the two leftmost BP samples $C(i-j)$ and $C(i-j+1)$ of the last processed interval (Fig. 2).

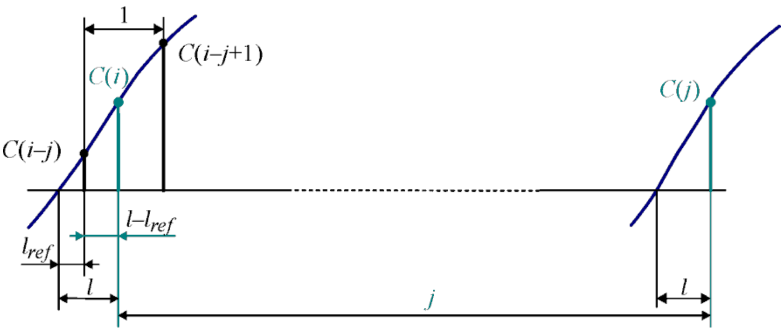

Fig. 2

The first new correction is

$$C(i) = C(i-j) + (C(i-j+1) - C(i-j))(l - l_{ref}),$$

where j is the distance between the current and the last processed interval, l_{ref} is the last determined left outside part, l is the current one. Each next correction $C(i+1)$ is determined by means of the already known $C(i)$. To avoid calculation errors when the $C(i)$ position is near the sine wave peak, this correction must be specified through the expression

$$C(i) = 2[C(i-j) - C(i-j-1)].$$

Similar formula is used for corrections with current number higher than N of the last processed interval.

Results

At the beginning some recordings with SR = 5 kHz were processed. Fig. 3 demonstrates the PLI elimination from the re-sampled AHA 1005d1signal, which is mixed by F changing from 49 through 51 Hz. The maximum absolute error committed is 17 µV, the first second of which is shown in Fig. 4 in zoomed scale. The error is computed all over the signals except for the edges of the recordings. As can be seen in the two next Figures, the PLI cannot be suppressed at the beginning of the AHA 1001d1 signal since it starts by QRS complex before being detected any liner segment. Other figures manifest the coincidence between PLI and BP filtered mixed signal during and after the transition process.

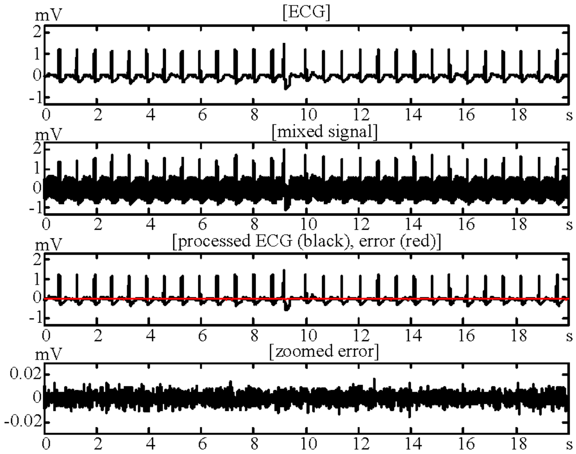

Fig. 3

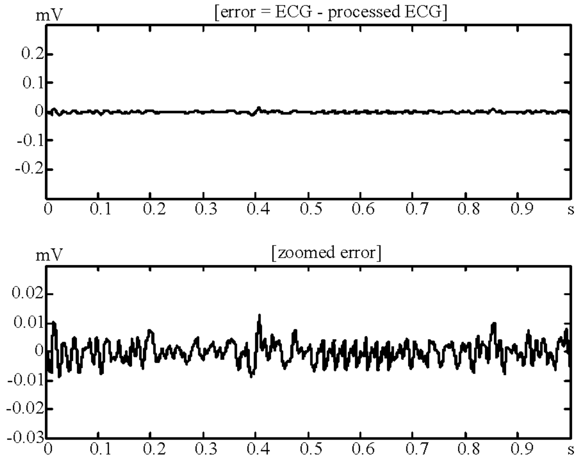

Fig. 4

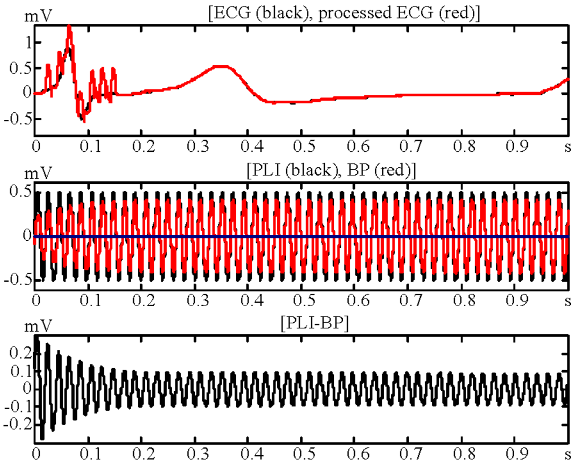

Fig. 5

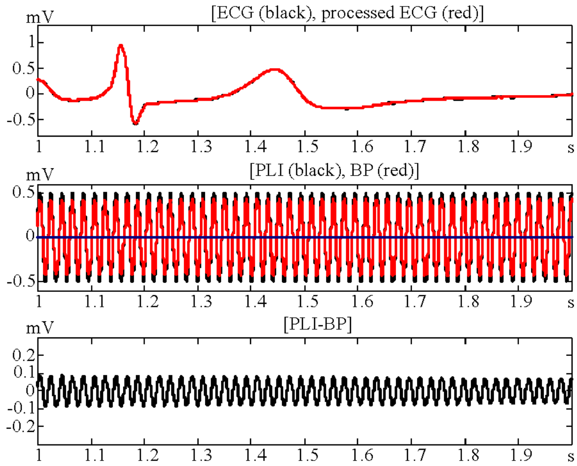

Fig. 6

The next tests were performed with paced ECG signals available in *PacedECGdb* [21] comprising a total number of 1404 recordings: 780 representing 'pure' ECG with pacing pulses and 624 that contain paced ECG contaminated by tremor, all of them with duration of 10 seconds. The pace pulses are with 7.8 to 102 μs rising edge duration and 102 to 2180 μs pulse duration. The amplitude is usually between 250 μV and 2 mV.

The first subplot of Fig. 7 shows the ECG paced signal p09_16_PacePulse_03_Kp=0.03125 demonstrating fixed-rate ventricular pacing. The pulses, some of them not effective, are with 250 μV amplitude as well as 31.3 μs rising edge and 320 μs pulse durations The second subplot represents synthesized PLI with SR = 128 kHz and variable F from 45.5 through 50.5 Hz for 5 s. Although the paced signal is announced as 'pure', one may observe residual noise, probably some kind of tremor that will corrupt the assessment of the PLI elimination from the mixed signal (the third subplot). Besides, the pace pulses are invisible there but will be totally flatted by any filtering procedure.

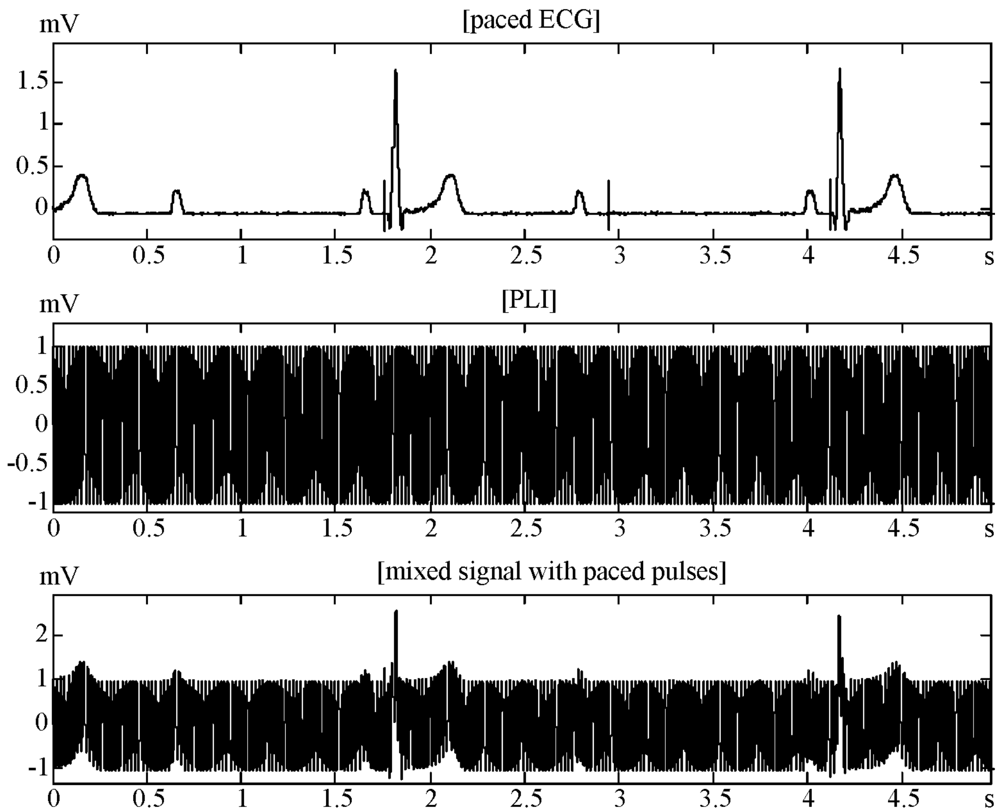

Fig. 7

Therefore, we proceeded as follows: the pace pulses were subtracted from the mixed signal; the corresponding parts were smoothed; the tremor was suppressed by comb filter with first zero at 35 Hz; the signal was then re-sampled down to 4 kHz and the PLI was eliminated; finally the re-sampled pace pulses were added back. Some of these steps are illustrated in Figs. 8 and 9. A peak of pace pulse (Fig. 8, first subplot) is detected as sample k, which is higher by 200 μV towards 3 previous samples $k-1$ to $k-3$ and lower than the 3 following samples $k+1$ to $k+3$. The pace pulse duration is defined by the sequence $k-5$ through $k+128$ (second subplot of Fig. 8). The mixed signal is smoothed by linear interpolation between the leftmost $k-5$ and rightmost $k+128$ samples, see the third subplot. All 3 pace pulses of the analyzed epoch are displayed at the bottom of the Fig. 8.

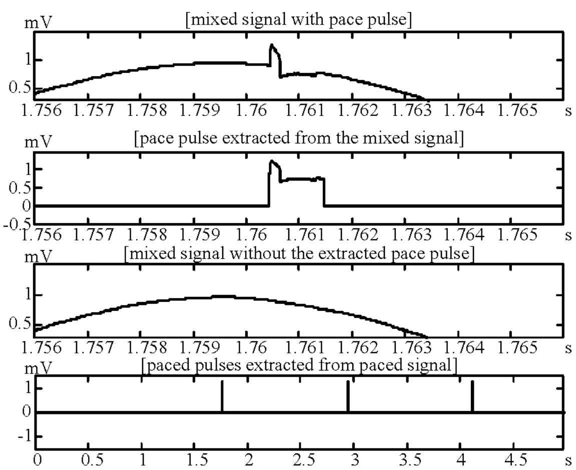

Fig. 8

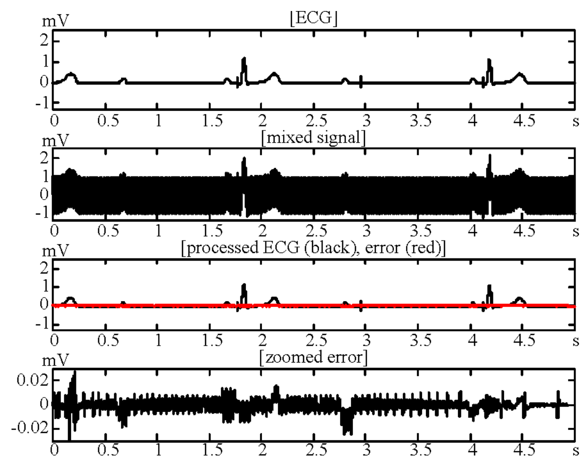

Fig. 9

The mixed signal (Fig. 9) is subjected to the subtraction procedure. The result is compared to the input ECG signal with suppressed tremor. The error committed is correctly evaluated as about 20 μV. The last two Figures 10 and 11 exhibit this error in zoomed scale along the 4th and 5th seconds of the recording.

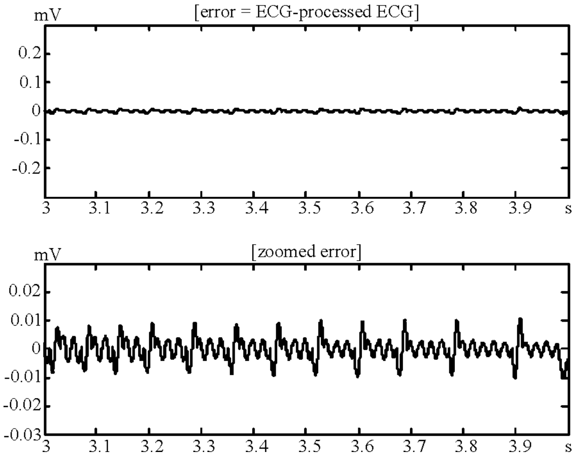

Fig. 10

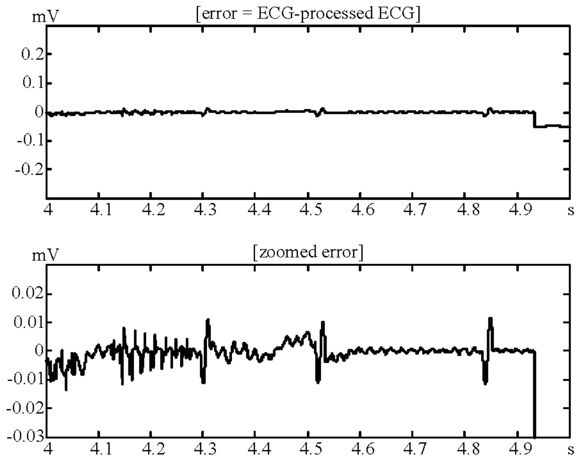

Fig. 11

The real sequence of steps proposed for removing the PLI from paced ECG signals, usually sampled with 128 kHz, is shorter than the above pointed out. The pace pulses are extracted from the contaminated (mixed) signal after that their intervals are smoothed. The mixed signal is re-sampled down to 4 (16) kHz and subjected to the subtraction procedure. The processing time is significantly reduced while at the same time the processed ECG keeps all useful information. A SR lower than 2.5 kHz will unacceptably reduce the PLI removing accuracy.

Discussion and Conclusions

The developed version of the subtraction procedure intended for high sampled signals is based on the ongoing analysis of sine waves available after BP filtration of the contaminated ECG signal with negligible phase shift. The calculated sample number, as well as the leftmost and rightmost parts outside the samples are successfully used for PLI removing both in linear and non-linear segments. The maximum absolute error obtained with 5 and 128 kHz sampled ECG signals is about 20 μV except for the edges of the recordings.

The proposed approach to PLI elimination from paced ECG recordings (usually sampled with 128 kHz or at least 16 kHz) includes pace pulse elimination, signal re-sampling down to 4 kHz and subtraction procedure implementation followed by adding back the pace pulses.

Methods

The PLI elimination from high sampled ECG signals is based on counting the samples within the ongoing sine waves. They are extracted from the contaminated cardiac activity by means of bidirectional band-pass filtration. The key component of the method is the evaluation of the two inter-sample lengths located at both ends of the sinusoidal curve. The sum of those lengths is usually lower than the unity accepted for the rated inter-sample interval. The obtained fractional number of inter-sample distances/samples is used further as divider of the contaminated ECG sample amplitudes summed along the processed sine interval thus increasing the accuracy of the determined central 'clean' ECG sample. This sample value is adjusted and shifted, if necessary, to match the nearest real position of corrupted ECG sample. The described approach is applied on the linear segments having frequency band near to zero such as PQ and TP intervals.

The differences between the corrupted and the 'clean' values, called corrections and related to the last sine wave of the linear segment (QRS complexes and high T waves) are used during the subsequent non-linear segments to eliminate the PLI from the samples according to their dislocation towards the corrections.

The paced ECG signals denoising require additional approach when applying the method described above. The lowest amplitude and duration of pace pulses may reach 250 µV and 100 µs, respectively. Therefore, the pulses have to be extracted and stored before the ECG signal is preliminary re-sampled down to 4 kHz and subjected to PLI elimination. Then the pulse paces are added back to the processed ECG signal.

Ethics approval and consent to participate.
Not applicable.

Consent for publication.
Not applicable.

Availability of data and materials.
The datasets analysed during the current study are publicly available.

Competing interests.
The authors declare no competing interests.

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Authors' contributions. ID developed the ongoing analysis of sine waves available after band-pass filtration of the contaminated ECG signals. TS worked on the pace pulses extraction from the paced ECG signals. GM contributed to the signal preprocessing including the band-pass filtration with negligible phase shift. All authors read and approved the final manuscript.

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Abbreviations
PLI: Power-Line Interference
FFT: Fast Fourier Transform
DWT: Discrete Wavelet Transform
RNN: Recurrent Neural Networks
SNR: Signal-to-Noise Ratio
MSE: Mean Square Error
SR: sampling rate

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Figures

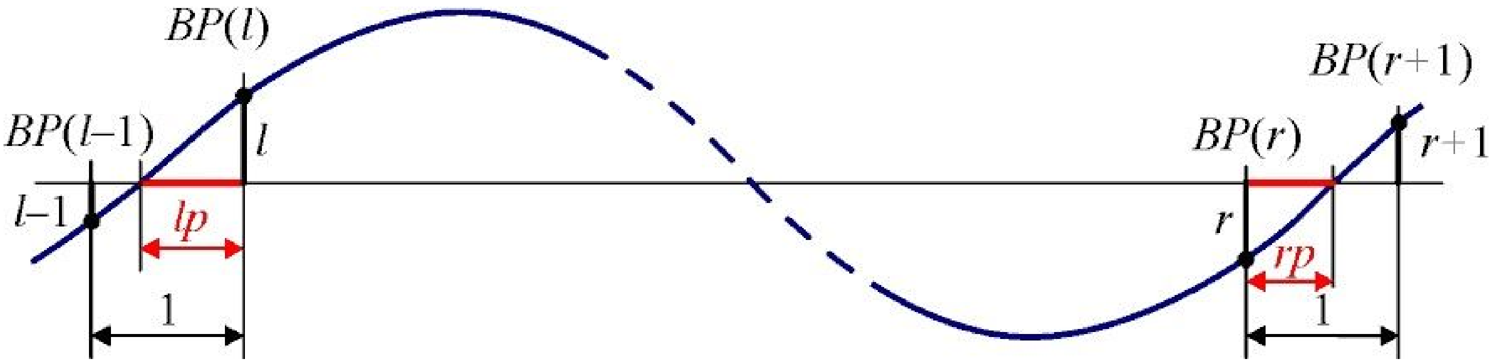

Figure 1

Figure 1

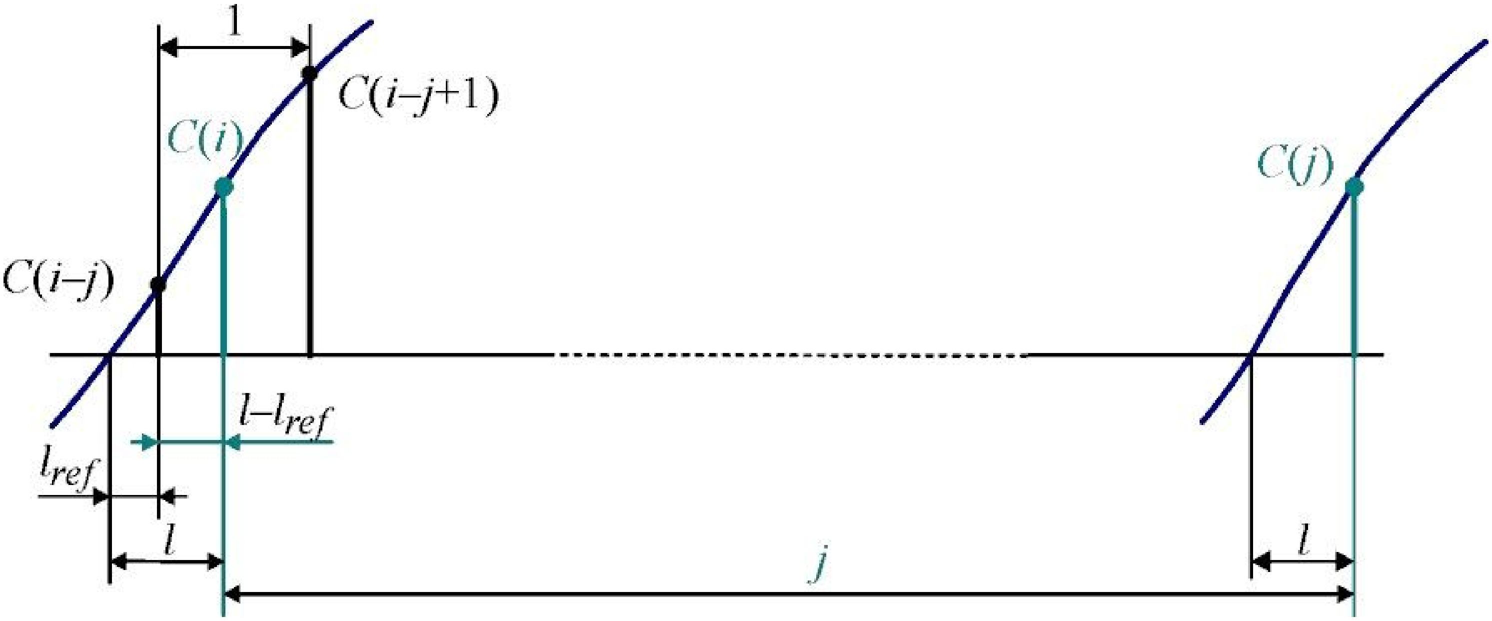

Figure 2

Figure 2

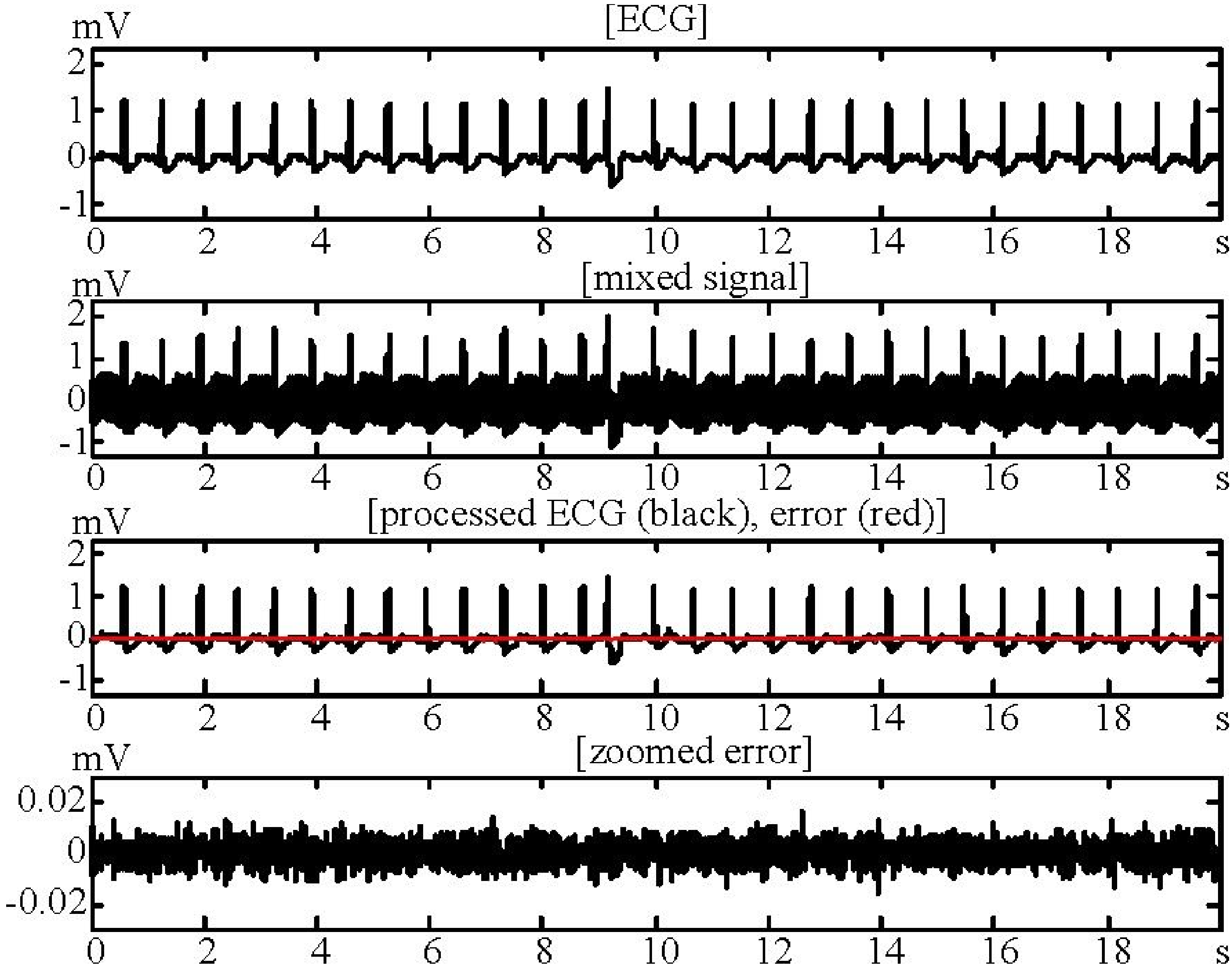

Figure 3

Figure 3

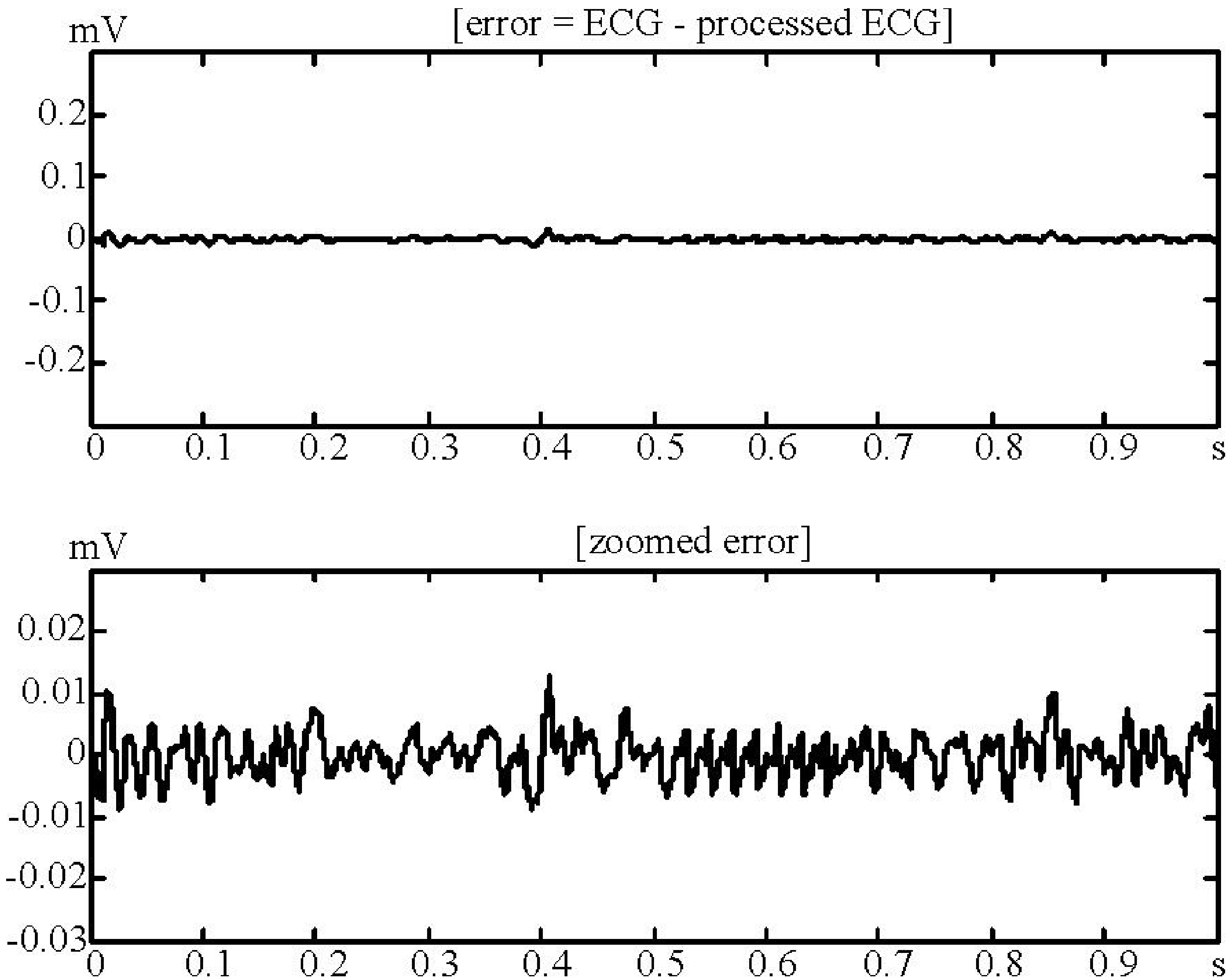

Figure 4

Figure 4

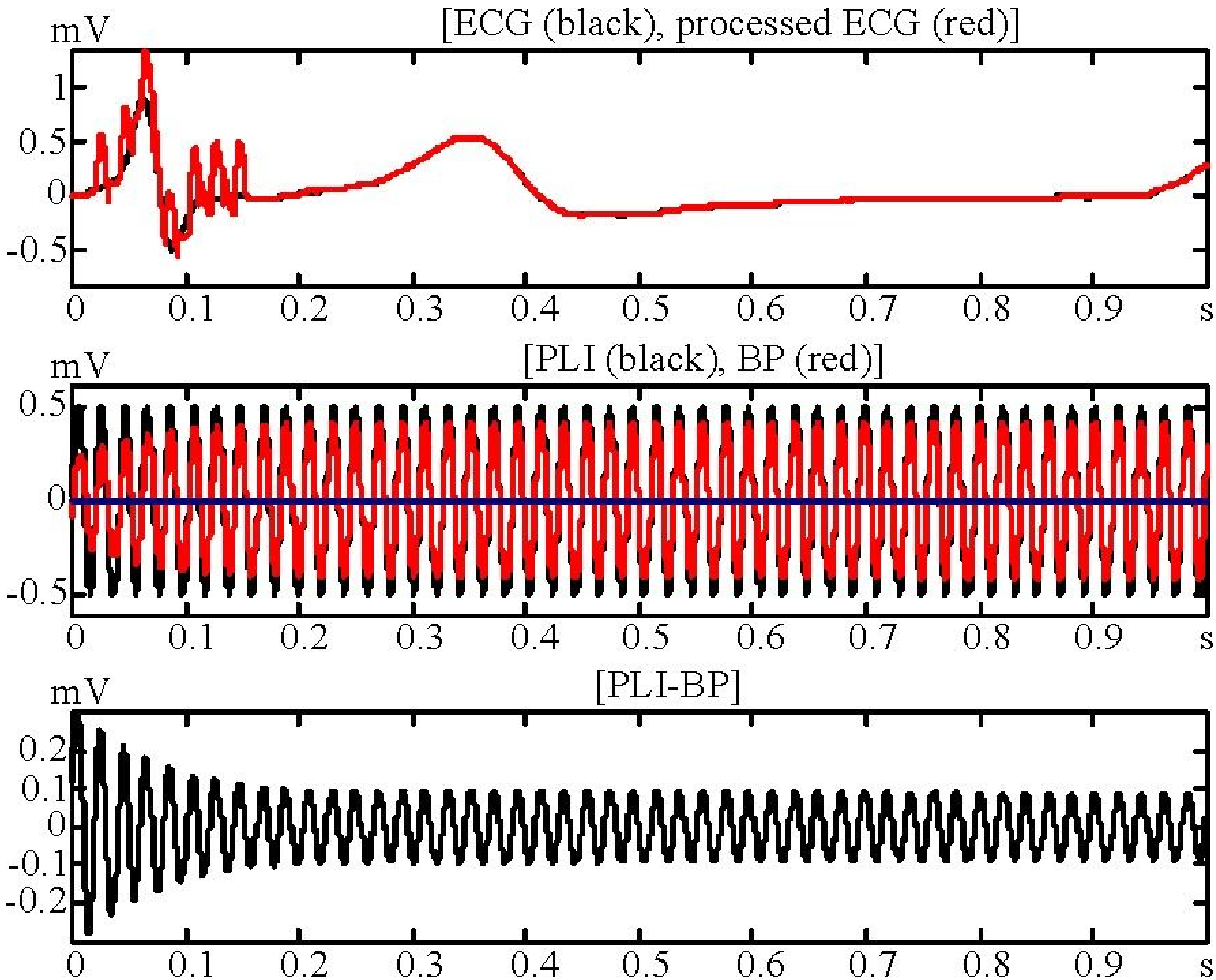

Figure 5

Figure 5

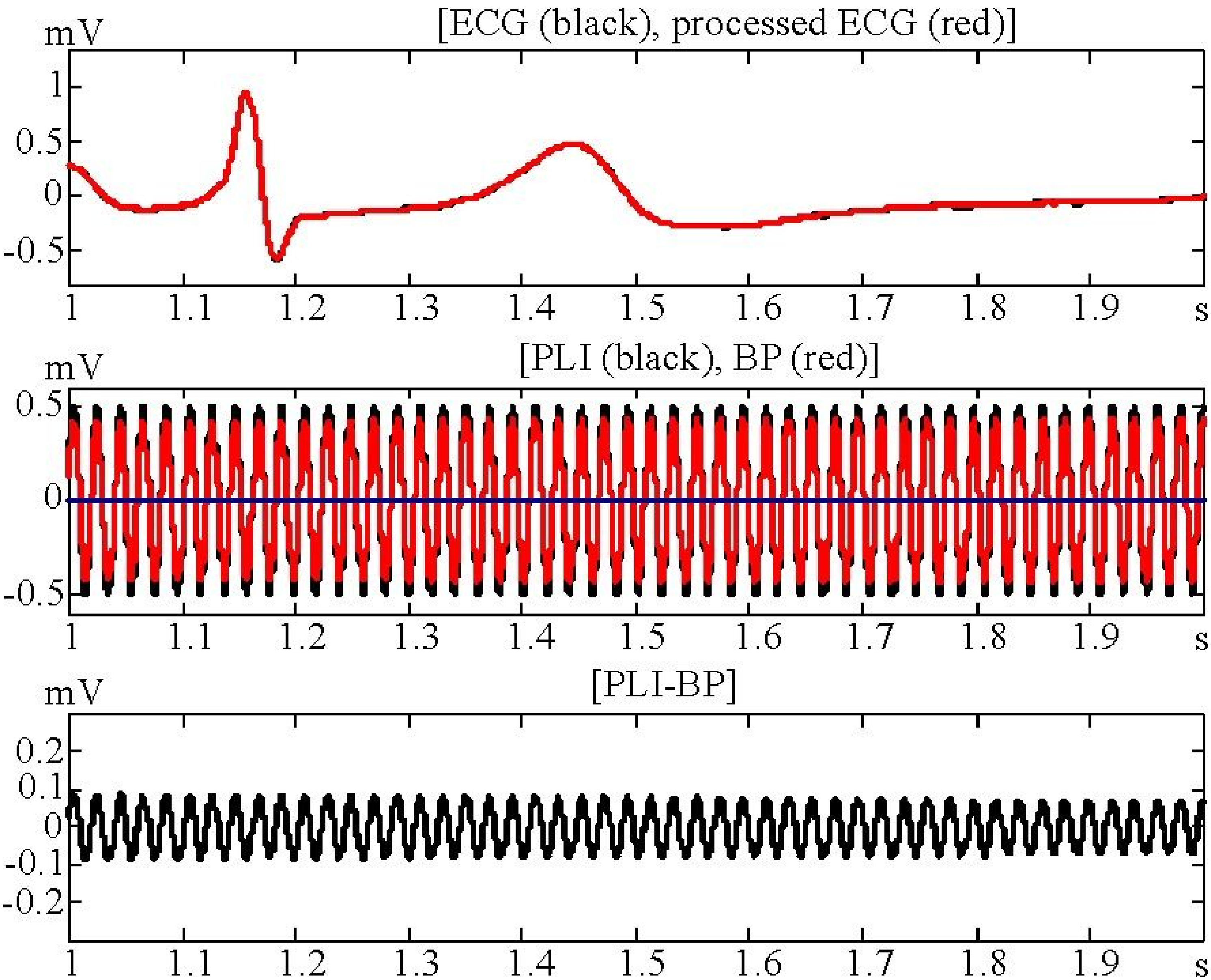

Figure 6

Figure 6

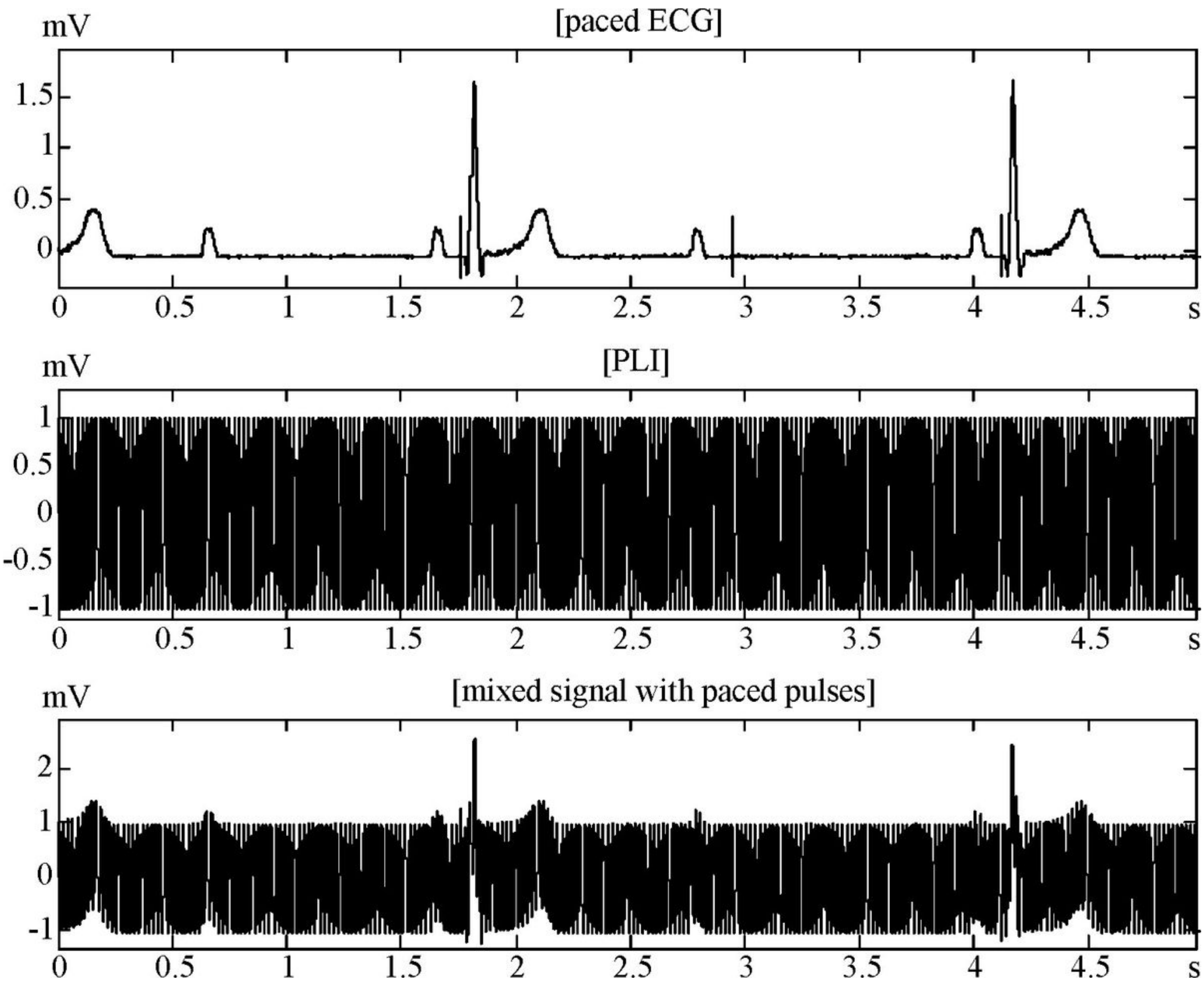

Figure 7

Figure 7

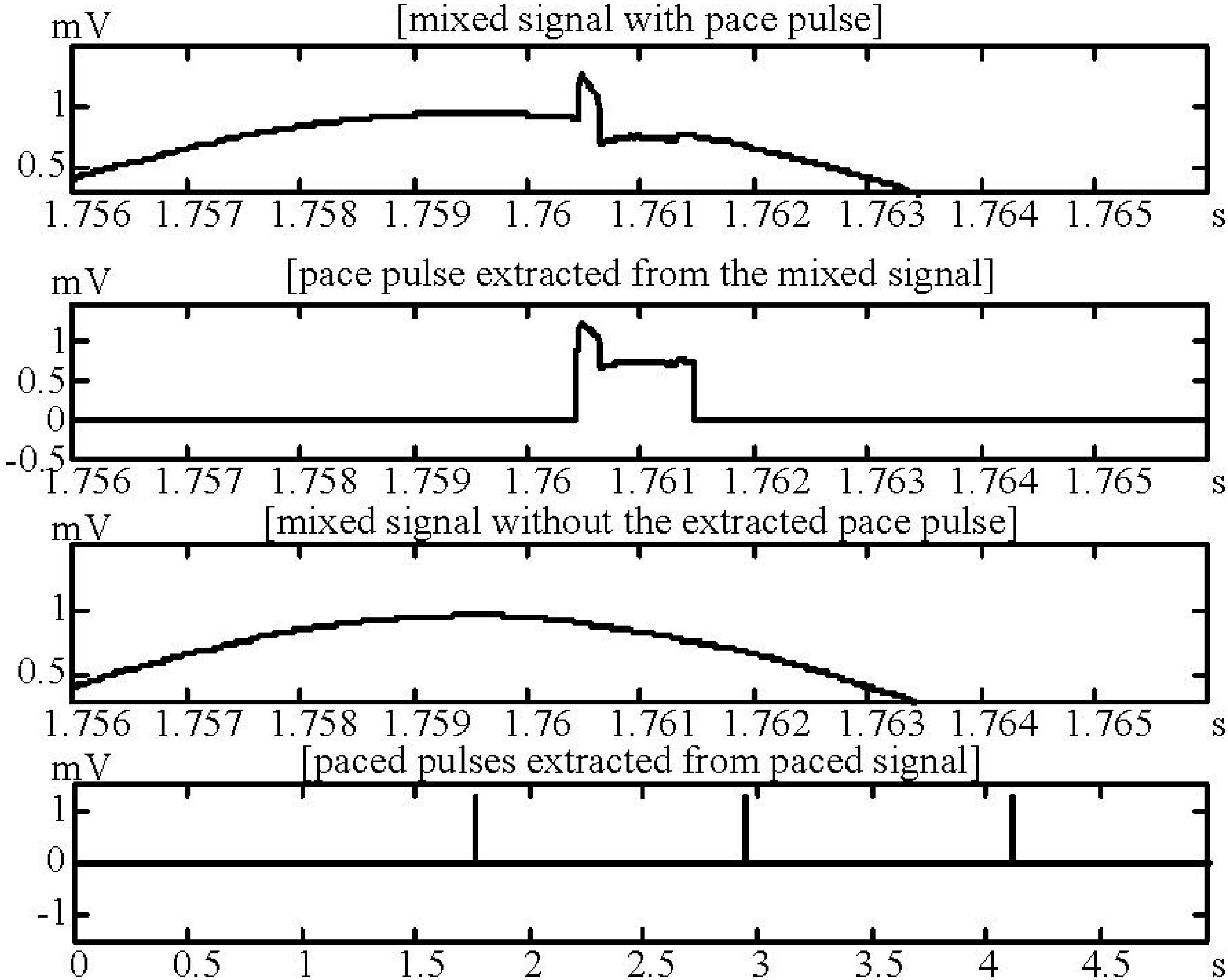

Figure 8

Figure 8

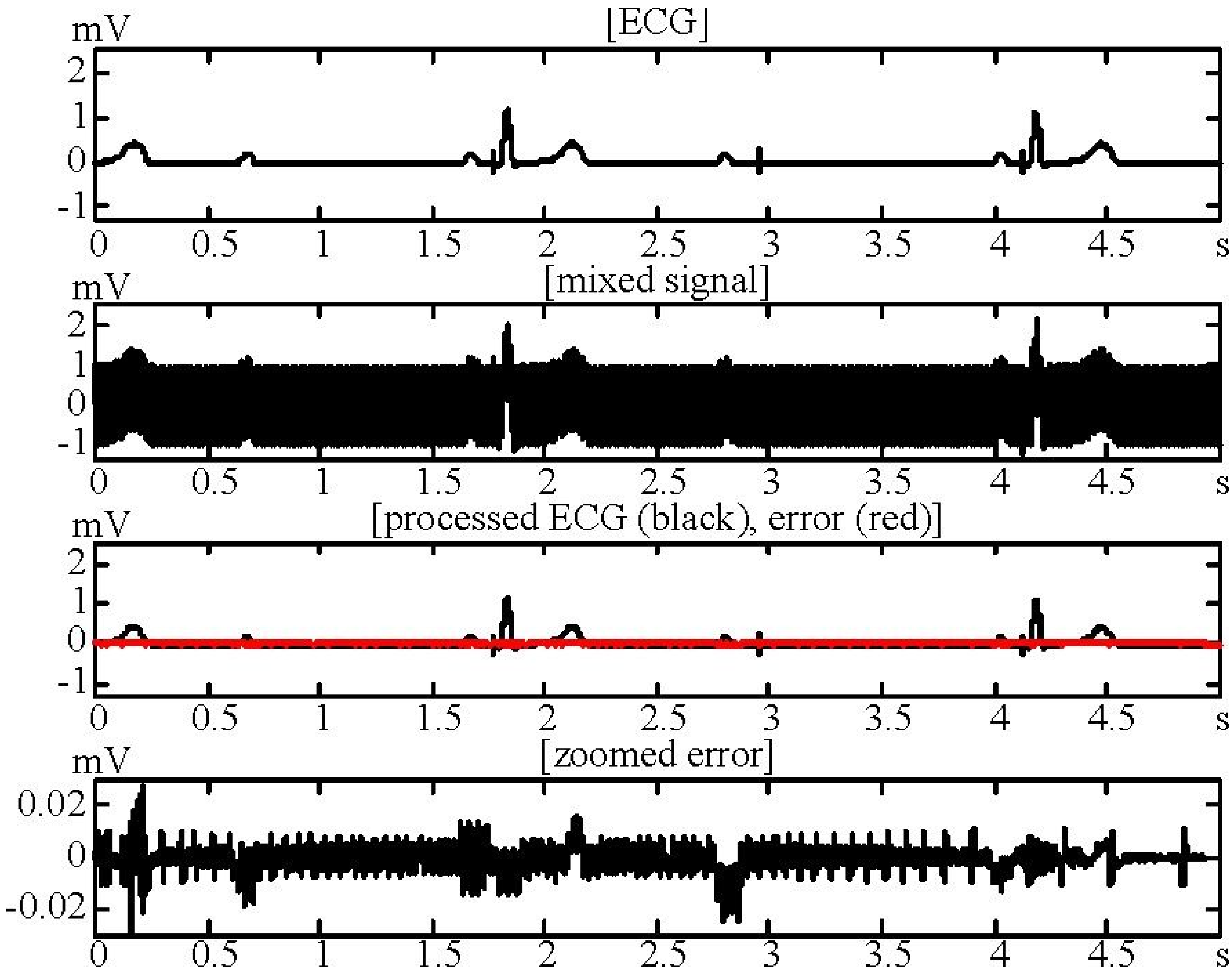

Figure 9

Figure 9

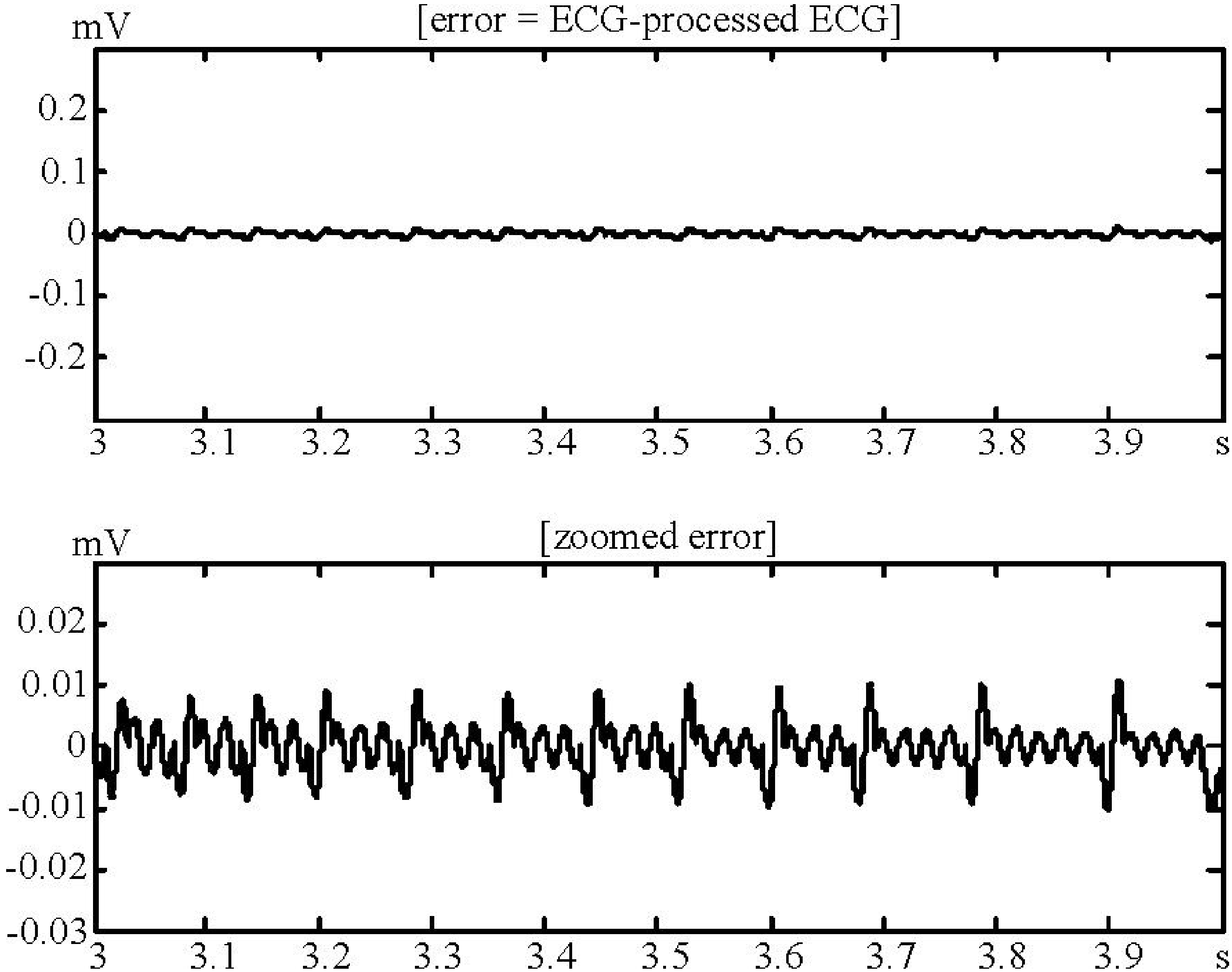

Figure 10

Figure 10

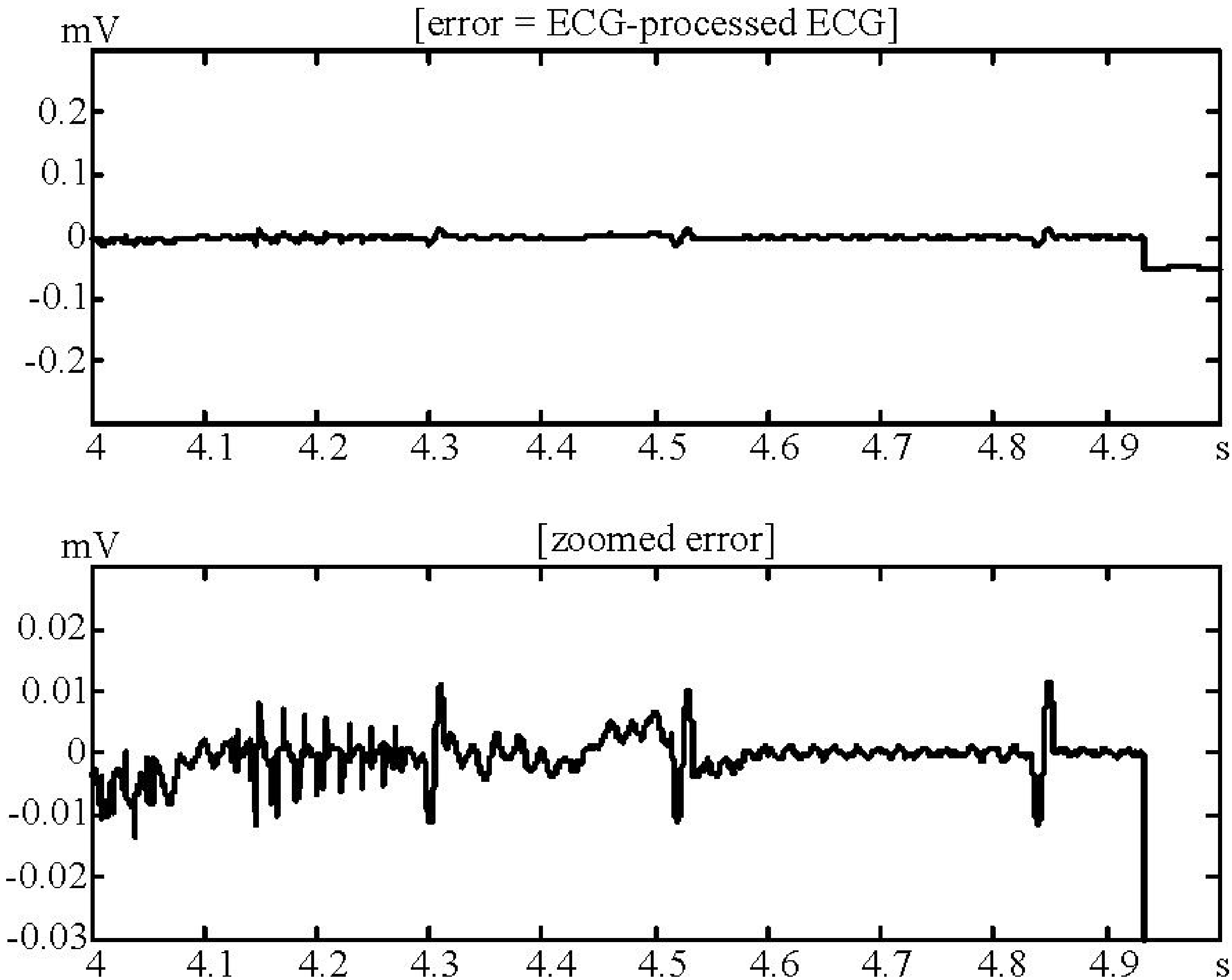

Figure 11

Figure 11