SUBTRACTION METHOD FOR POWERLINE INTERFERENCE REMOVING FROM ECG

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In Memoriam of Professor Ivan Konstantinov Daskalov

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This paper presents the subtraction method for interference cancellation in ECG. In contrast to the well-known hardware and software filters, the method does not affect the signal frequency components around the rated powerline frequency. The method searches for linear segments in the ECG signal. Then a digital filter is used to remove the interference from these segments. The samples of the interference signal are computed in these segments and later on these samples are used to remove by subtraction the interference from the signal where non-linear segments are encountered. A theoretical generalised approach of the method is developed in the paper.

1. INTRODUCTION

The origin of the method is dated from 1979. A contract has been made between Technical University – Sofia and Institute of Medical Technology Sofia for development of a "Microprocessor Electrocardiographic Selector for Screening Analysis". The manager of the contract was prof. V. Zlatarov, responsible for the design – R. Ivanov and design engineer – G. Mihov. A collaborator was the Central Laboratory for Specialised Electromedical Instrumentation – director prof. I. Daskalov and Ch. Levkov and M. Matveev as a research team.

One of the main problems in technical electrocardiography is the removing of the PowerLine interference (PLI). Various FIR filters were tested on the real ECG signals. The sampling rate was 250 Hz with 8 bit ADC. MC6800 (Motorola) was used as a processing unit. The software was written on assembly language and compilation was performed by hand or on a cross-assembler on a mainframe computer.

The preliminary analysis showed that PLI is removed satisfactory but the shape of the ECG signal is distorted due to the attenuation of important frequency components in the region of QRS complex. It was noticed that in the region of P and T waves the distortions are very low due to the low frequency components in these segments.

It was decided to perform the digital filtration only in these segments where the

ECG signal is not distorted. At the same time an extraction of the PLI signal from these points and saving in temporary memory buffer should be performed. Further on the information in this buffer will be used to subtract the PLI from these segments where the digital filtration does not give results – QRS complex for example.

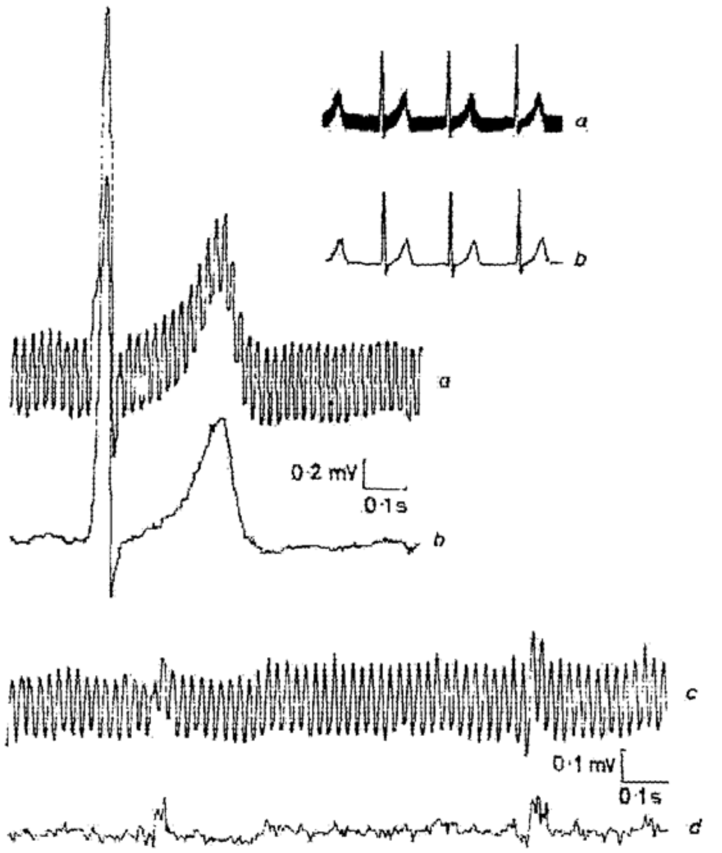

Fig. 1. One of the first results obtained by subtraction method.

G. Mihov realised the idea. The first results were very promising (Fig. 1). Everybody involved in the project was very enthusiastic and the experiments were continued in order to improve the method. A clean artificial ECG signal was added to PLI signal in order to evaluate the errors and the method efficiency. These experiments showed that the efficiency of the method is very sensitive to synchronisation between PLI frequency and sampling rate. A hardware synchronisation to the PLI frequency was developed. Due to the low processing power the method was used only off-line.

The subtraction method for removing powerline interference from ECG was completed at the end of 1980 and a Bulgarian patent was issued [Levkov et al., 1980, 1]. The first publication of the method was in 1981 [Daskalov et al., 1981, 2] and the first practical implementation was in "ECG Selector for Screening Analysis" [Daskalov et al., 1981, 3]. This method was the main topic in Ph.D. thesis of G. Mihov [Mihov, 1983, 4]. A paper published in recognised international journal presented the results to the wide scientific society [Levkov et al., 1984, 5].

Since 1980, the subtraction method has been widely implemented in many thousands of microcomputer based ECG instruments produced in Bulgaria. The method was further improved [Christov and Dotsinsky, 1988, 6], which widened the possible applications.

2. THE METHOD

In the first version the subtraction method has been applied with a sampling rate which is multiple and hardware synchronised to the frequency of the PLI.

The basic sequence for the application of the method includes the following stages:

– *Linear segment detection*. Every ECG signal sample is tested whether it belongs to linear segment. A criterion for linearity is developed which is insensitive to the PLI.

– *Interference extracting*. If the linearity criterion is fulfilled a FIR filter is performed in these segments to remove the PLI. The PLI signal is obtained by subtracting filtered samples from the original signal samples.

– *Interference restoring*. The PLI samples are stored in an *Interference temporary FIFO buffer*. They are updated every time when a linear segment is found. These samples are used later on to subtract the PLI from ECG signal.

– *Interference subtracting*. In the non-linear segments where the linearity criteria is not fulfilled the PLI is removed by subtracting the samples in FIFO buffer from the original signal. A phase relationship between PLI samples and signal samples must be considered when this procedure is performed.

A flow chart of the method is shown on Fig. 2.

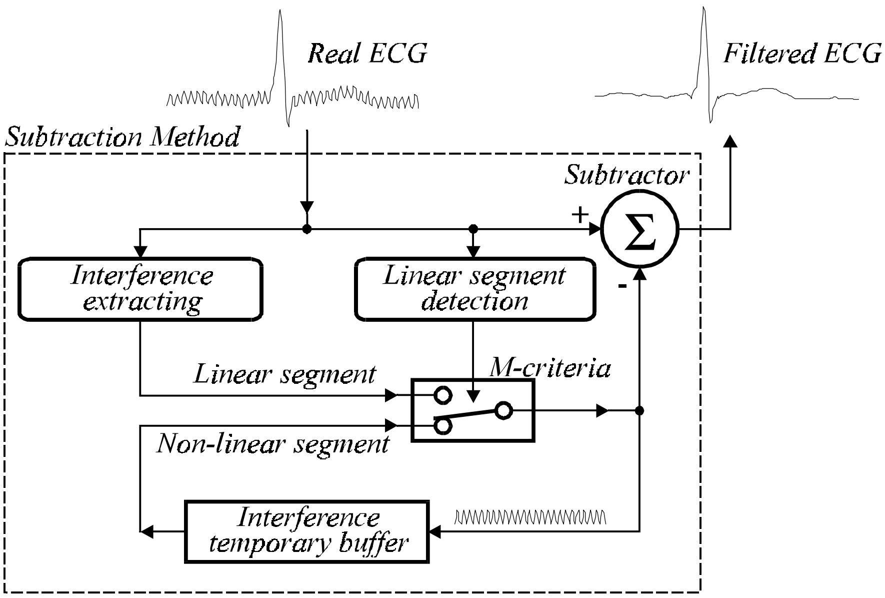

Fig. 2. Basic structure of the subtraction method.

In the multiple sampling case in each PLI period there are integer number of samples $N = \Phi/F$. Here F is the interference frequency and Φ is the sampling rate. N may be odd $N = 2n + 1$ (odd multiplicity) or even $N = 2n$ (even multiplicity), n being an integer. In non-multiple sampling case N is a real number.

2.1. Linear segment detection

Typical linear and non-linear segments are shown on Fig. 3.a. Real ECG signal (trace *a*) is superimposed by interference (trace *b*). The linear segments include low frequency and power-line frequency components. An approximate frequency spectrum of such linear segment is shown on Fig. 3.b.

The linear segment detection is based on second difference of the signal (noted by D_i). It is compared with a certain threshold M, i.e. $|D_i| \le M$. If the $|D_i|$ is less than M this segment is assumed linear and the PLI samples can be extracted with high accuracy.

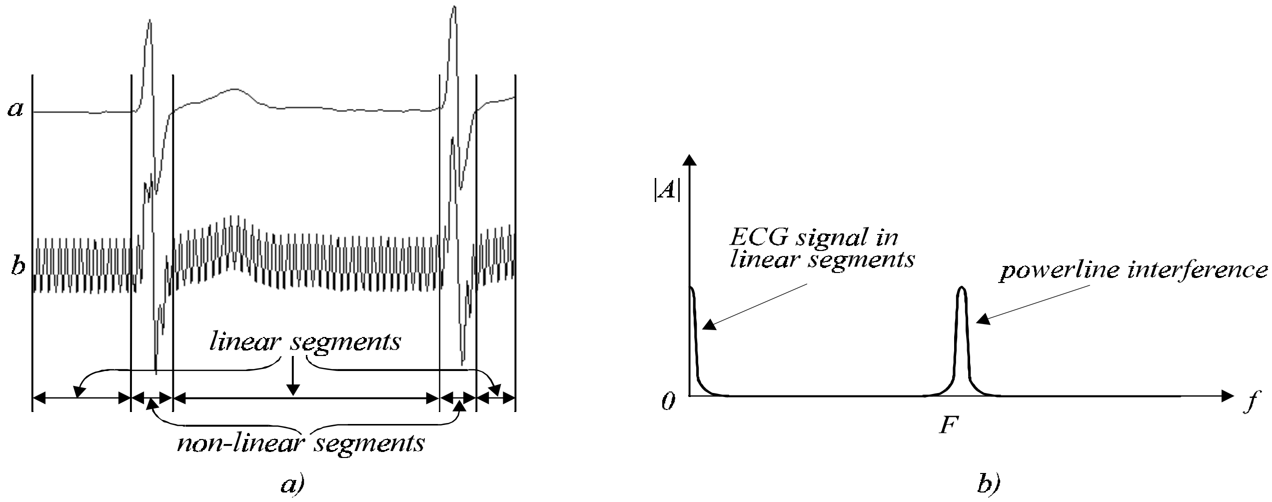

Fig. 3. a:Typical linear and non-linear segments of a real ECG signal; b: Approximate frequency spectrum of a linear segment.

M value is empirically obtained and it determines the permissible error. The less *M* is, the less is the error but from the other side the probability to find a linear segment is reduced. The proper value for *M* has been obtained after numerous experiments. The action of the linearity criteria has been shown on Fig. 2 as a switch *M-criteria.*

The first differences are always performed in interval equal to the period of PLI in order to eliminate PLI influence. There are different variants when the second difference is computed and also variants in comparison to threshold *M*.

Fig. 4 shows a linear segment consisting of straight line and PLI. Theoretically, it has D_i equal to zero. The symbol τ stands for the sampling period, i.e. τ = 1/Φ.

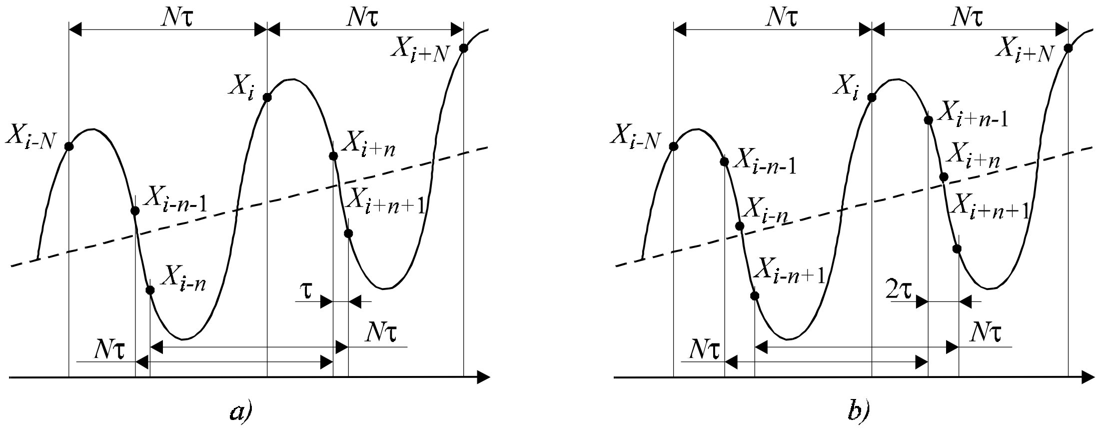

Fig. 4. Linear segments with D_i = 0.

The first experiments were performed with second differences computed from the first differences that are symmetrically located around the processed sample [2]. The difference which requires maximal length of two periods 2*N*τ of PLI is:

$$D_i = \left(X_{i+N} - X_i\right) - \left(X_i - X_{i-N}\right). \qquad (1)$$

Symmetrical differences that require minimal length for analysis can be with odd and even multiplicity:

$$D_i = (X_{i+n+1} - X_{i-n}) - (X_{i+n} - X_{i-n-1}), \quad (2)$$

for odd multiplicity (Fig. 4.a), with length of the analysed segment $(N+1)\tau$ and

$$D_i = (X_{i+n+1} - X_{i-n+1}) - (X_{i+n-1} - X_{i-n-1}), \quad (3)$$

for even multiplicity (Fig. 4.b) with length of the analysed segment $(N+2)\tau$. In the above equations i is the current sample number and X is the sample amplitude.

More complicated approach can be used to obtain the second difference [4, 5]. N+1 successive first differences are computed. The maximal and minimal first differences are taken to compute the second difference criteria.

$$\begin{aligned} D_i = max\{(X_{i+N} - X_i),(X_{i+N-1} - X_{i-1}),\dots,(X_i - X_{i-N})\} - \\ - min\{(X_{i+N} - X_i),(X_{i+N-1} - X_{i-1}),\dots,(X_i - X_{i-N})\} \end{aligned} \quad (4)$$

This criterion gives very good results but needs more computation time.

After the experiments the optimal M value was chosen to be equal to 8 for 8-bit ADC wit 20 μV weight of the LS bit referred to the input of the ECG amplifier. That means that M is 160 μV.

Another criteria suggested in [6] is based on computation of two consecutive first differences:

$$D_i = (X_{i+N+1} - X_{i+1}) - (X_{i+N} - X_i), \quad (5)$$

Here the condition $|D_i| < M$ must be confirmed N times in order to assume that the tested segment is linear. Optimal M was empirically obtained after experiments and has a value of 12 (150 μV referred to the input). Later on in a paper [Dotsinsky and Daskalov, 1995, 7] this criteria was defined as:

$$D_i = (X_{i+N+2} - X_{i+2}) - (X_{i+N} - X_i), \quad (6)$$

Where M is equal to 8 (100 μV referred to the input). This approach makes the transition linear-non-linear segment more precise.

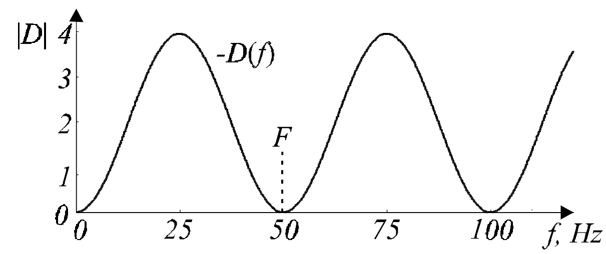

Fig. 5. Transfer function of *D*-filter for *F* = 50 Hz.

In 1995 in the work of [Mihov, 1995, 8] the linearity criteria was interpreted as digital filter used to estimate the signal spectrum. The linearity criteria is named D-filter and for the first time a firm theoretical background was given to previously somewhat empirical approach [Georgieva and Mihov, 2002, 9]. Fig. 5 shows the transfer function of the D-filters according to Eqn. (1).

The spectral approach for linearity criteria is very useful and the requirements for the criteria can be defined easily in the frequency domain. The D-filter must have zeros in transfer function for $f = 0$ and $f = F$. The transfer function can be represented as:

$$D(f) = -4\, sin^2 \frac{2\pi fn}{\Phi} \quad (7)$$

In the case where the sampling frequency is not multiple to the PLI frequency the D-filter can not reject sufficiently the PLI. In the spectral estimation there is a residual component D_F. Using the frequency interpretation in the paper of [Mihov, 1996, 10] a modification of the linearity criteria was proposed. The modification has two components:

– An auxiliary FIR filter A_i with transfer function zero in $f = 0$ and gain A_F for $f = F$ is synthesised. Then this filter is modified into another filter A^*_i by scaling with coefficient D_F / A_F. In this way the gain of the new filter becomes equal to D_F at frequency $f = F$;

– The transfer function of the scaled auxiliary filter is subtracted from the D-filter function:

$$D_i^* = D_i - A_i \frac{D_F}{A_F} \tag{8}$$

2.2. Interference extracting

The PLI from linear segments of the ECG signal can be removed by different type of filters (later denoted as K-filters). In general case symmetric FIR filters of type $\sum_{j=-N}^{N} a_j X_j$ are used. Since these filters are used only in segments where frequency components are concentrated around $f = 0$ and $f = F$ (see Fig. 3) the requirements are simple: transfer function with zero in $f = F$, unity gain in $f = 0$ and linear phase response.

The first used K-filter is a moving average FIR filter [8, 9] with one PLI period as window (in case of odd multiplicity sampling). The equation describing such a filter is:

$$Y_i = \frac{1}{2n+1} \sum_{j=-n}^{n} X_{i+j}\ , \tag{9}$$

and the transfer function equation is:

$$K(f) = \frac{1}{2n+1} \frac{sin \dfrac{\pi(2n+1)f}{\Phi}}{sin \dfrac{\pi f}{\Phi}} \tag{10}$$

Here X_i and Y_i represent original and filtered samples, respectively.

Later on in [6] another FIR filter was proposed for the case where even number of samples is included in the PLI period. For this case of even multiplicity sampling a theoretical analysis has been made in [7]. Only one of these filters has linear phase response. Nevertheless these filters can be used successfully since they are applied

$$Y_i = \frac{1}{2n} \left[\sum_{j=-(n-1)}^{n-1} X_{i+j} + \frac{X_{i-n} + X_{i+n}}{2} \right], \tag{11}$$

with transfer function:

$$K(f)=\frac{1}{2n}\left(\frac{sin\frac{\pi(2n+1)f}{\Phi}}{sin\frac{\pi f}{\Phi}}-cos\frac{2\pi fn}{\Phi}\right) \tag{12}$$

The advantage of these filters is that computation equation needs N additions and only one division. The number of additions is proportional to the sampling rate.

In order to reduce computations, a more simple filter might be used [Levkov and Mihov, 1996, 11]. If the number of samples N in one period of PLI can be represented as a product of two integers $N = rq$ then the averaging can be performed only for r samples taken at every q-th sample. The smallest value is $r = 2$ and $N = 2n$. Then this filter has the following equation:

$$Y_i=\frac{X_{i-n}+2X_i+X_{i+n}}{4}, \tag{13}$$

and the transfer function is:

$$K(f)=cos^2\frac{\pi fn}{\Phi} \tag{14}$$

This filter was named 3-point filter since always 3 samples are used for computation independently of the number of samples in one PLI period. Fig. 6 shows the transfer functions of used K-filters – Eqns. (10, 12, 14).

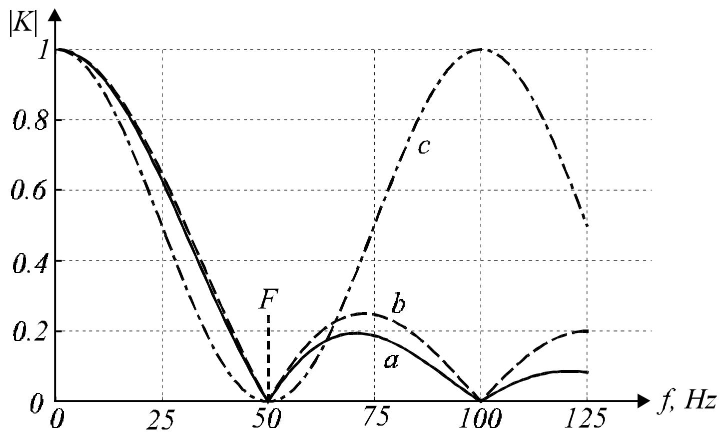

Fig. 6. Transfer function of *K*-filter: curve *a* – Eqn. 10, *n* = 2, Φ = 250 Hz; curve *b* – Eqn. 12, *n* = 4, Φ = 400 Hz; curve *c* – Eqn. 14, *n* = 3, Φ = 300 Hz.

In the case where the sampling rate is not multiple to the PLI frequency these filters can not be used since the condition $K(f) = 0$ is not true for the PLI frequency. In order to override this limitation in [8, 10] a method for correction of the filter difference equations is proposed. This correction has two stages:

– The filter transfer function is moved along Y axis with $-K_F$ value. In this way the transfer function obtains a zero for $f = F$ (curve b). In the difference equation this is equal to subtraction of the current sample X_i, multiplied by K_F, e.g $Y_i - K_F X_i$;

– A scaling is performed by multiplication with coefficient $1/(1 - K_F)$ in order to make the transfer function equal to 1 at $f = 0$ (curve c).

The new difference equation is:

$$Y_i^*=(X_i-Y_iK_F)\frac{1}{1-K_F}. \tag{15}$$

The coefficient K_F is computed beforehand from the equations of the transfer function of the filter [10, 12, 14].

The filters used to remove PLI in linear segments can be used to create an auxiliary filter for linear criteria correction.

$A_i = X_i - Y_i$ and

$$A_F = 1 - K_F \,. \tag{16}$$

When the PLI is removed in the linear segments at the same time the samples of the PLI signal are extracted and saved in a temporary FIFO buffer. The interference samples B_i are currently calculated by:

$$B_i = X_i - Y_i \,. \tag{17}$$

Equation (17) actually defines a digital filter, later denoted as (1-K)-filter.

2.3. Interference restoring

The extracted interference component is saved in FIFO buffer with size N at position, which corresponds to the ongoing phase of the powerline voltage. In case of multiple sampling, the interference is cancelled by simple subtraction only in these segments where the linearity criteria is not true. The interference signal with appropriate phase is taken from the buffer and then is subtracted from the original signal.

Considerable changes are necessary for the FIFO buffer organisation in the case of non-multiple sampling. A phase difference appears between the ongoing samples of the ECG signal and the buffer samples. To compensate this difference, an additional procedure for interference restoring has to be included in the subtraction method. This additional procedure must modify the samples B_i before their subtraction from the ECG signal in the non-linear segments. Such a procedure has been proposed by [Mihov, 1996].

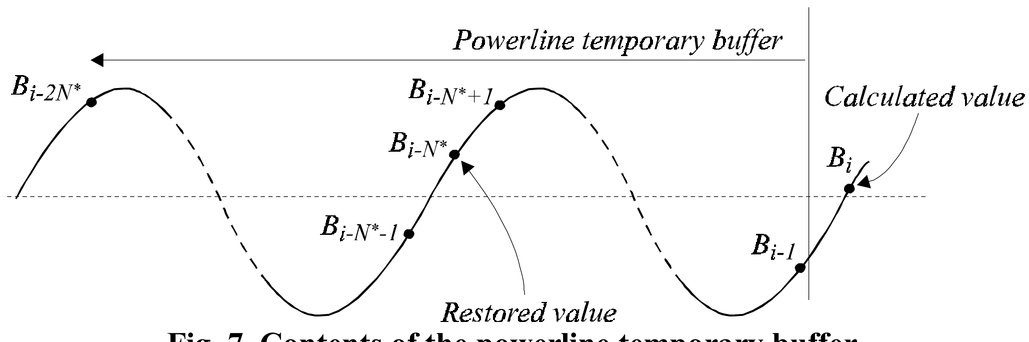

Fig. 7. Contents of the powerline temporary buffer.

A digital FIR filter of type $\sum_{j=-2N^*}^{0} a_j B_{i+j}$ (late denoted B-filter) is applied around the sample B_{i-N^*} in the temporary buffer (see Fig. 7) with a window $2N^*$, approximately equal to two interference periods (N^* is the rounded value of N). As a result the value of the interference is obtained in the middle of the window, multiplied by the gain of the filter at frequency F (denoted as B_F.). From the equation $B_F B_{i-N^*} = \sum_{j=-2N^*}^{0} a_j B_{i+j} = \sum_{j=-2N^*}^{-1} a_j B_{i+j} + a_0 B_i$ the value of the new compensated interference sample can be computed:

$$\sum_{j=-2N^*}^{0} a_j B_{i+j} \tag{18}$$

This procedure needs FIFO buffer size of $2N$ samples. Later on in [Mihov et al., 2004] this procedure is implemented in buffer with size N.

2.4. Interference subtracting

For the linear segments the filtered ECG samples are obtained directly in the stage of interference extracting by equations (9, 11, 13). In non- linear segments they are computed by subtraction:

$$Y_i = X_i - B_i . \tag{19}$$

3. EXPERIMENTS AND RESULTS

The subtraction method has been applied on various real ECG signals – 8 standard leads, holter records and American Heart Association ECG database are used. Fig. 1 shows one of the first applying of the subtraction method. This is a case with odd sample multiplicity (threshold M = 160 µV, F = 50 Hz and Φ = 250 Hz [5] and simple linear segment recognition). On Fig. 8 faster and optimised algorithm for linear segment detection is applied with even multiplicity, M = 160 µV, F = 50 Hz and Φ = 400 Hz [6].

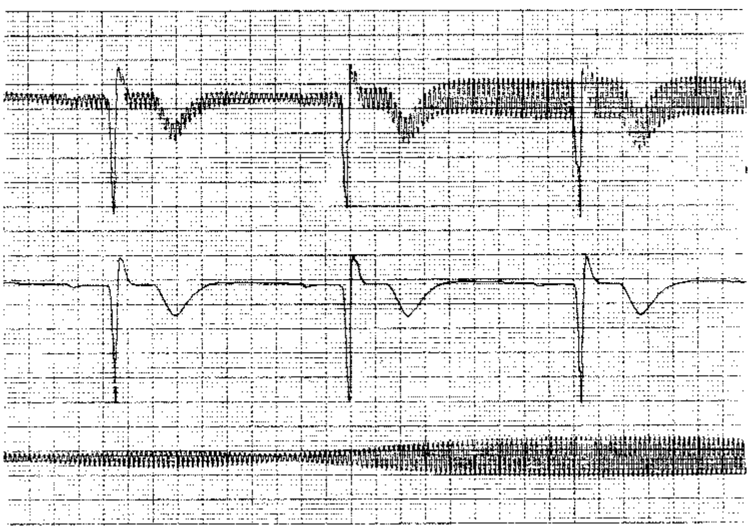

Fig. 8. First channel: simulated ECG signal with amplitude-varying interference; second channel: filtered signal; third channel: eliminated interference.

The software realisation of the subtraction method has been performed in different languages and computer platforms. Assembler, FORTH, C, and Matlab are some of them. The hardware implementations include MC6800, MC6803, HD6303, MC68HC11, ADSP2181 and IBM PC.

The main approach to the testing the efficiency of the subtraction method is as follows:

– There must be a "clean" ECG signal. To this signal is added PLI (synthesised or recorded).

– The subtraction method is applied to this signal.

– Then the difference between original "clean" signal and filtered signal is made. The obtained "error" signal can be analysed visually or statistically.

The example on Fig. 9 represents the application of the method in non-multiple sampling case. The same clean ECG signal is used with sampling rate of 250 Hz. A sinusoidal PLI is synthesised with $F = 60$ Hz. A 3-point K-filter, corrected D^*-filter and B^* filter that is applied to the samples in temporary buffer are used. The residual error signal amplitude is ±0.01 mV.

A large experimental verification of the method has been performed in 1986/87 with real ECG database [12].

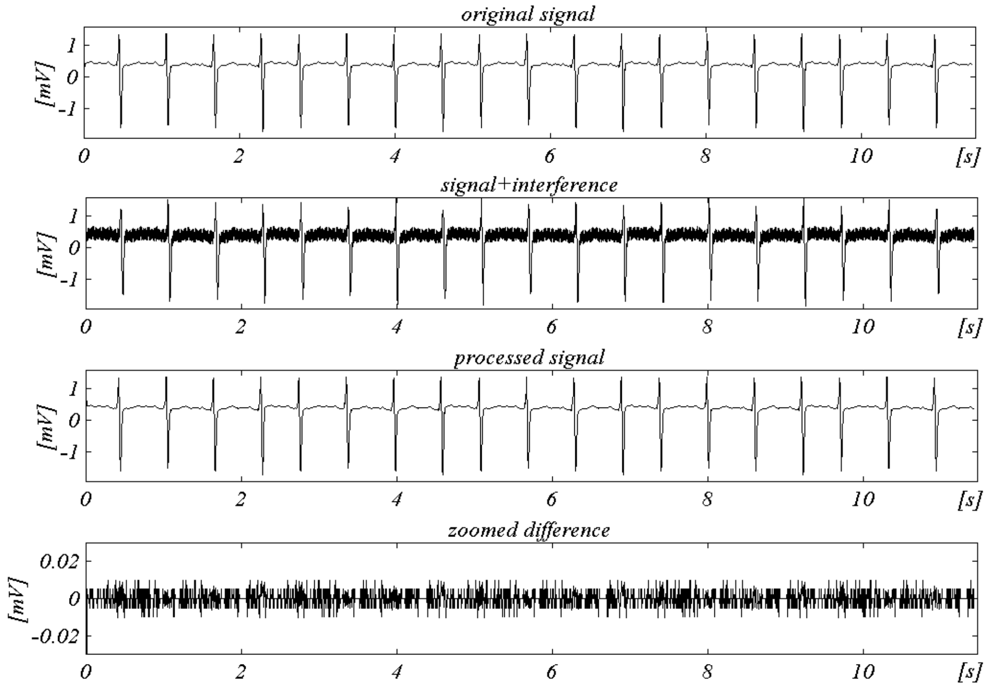

Fig. 9. Example for non-multiple sampling, F=60 Hz and Φ=250 Hz.

The results have been evaluated visually and statistically including expert reviews by qualified cardiologist. The database consists of 395 patient records (the 8 linearly independent standard leads) with 2.8 s duration, 250 Hz sampling rate and 20 μV weight of the LS bit of the ADC. The *M-criteria* was equal to 8. The records have been taken in real clinical environment without additional efforts to reduce the interference. Approximately 30% of the records were from healthy persons. The left records are typical patients of a cardiological clinic with various ECG abnormalities. The final conclusion was that this method could be recommended for application in everyday clinical practice.

4. DISCUSION AND CONCLUSIONS

The paper represents retrospectively the origin and evolution of the subtraction method for removing powerline interference from the electrocardiogram. A theoretical approach is made and all main steps of the algorithm are presented.

In all the years from its origin the subtraction method is improved and analysed. More than 6 Ph.D thesises have treated the method (including four of the authors

[Mihov, 1983, 4; Levkov, 1987, 12; Dozinski, 1986, 13; Christov, 1988, 14]). Scientific papers are published in recognised international journals. The method has been applied and improved in many papers by the international scientific community (Bulgaria, Germany, France, China, USA, Canada etc.) Some improvements and new applications of the method can be find in the papers of [Yan, 1993, 15], [Gang et al., 1995, 16], [Monaco, 2000, 17] – in the last paper the method has been implemented in Pascal language. This method was also applied to other signals where linear segments can be identified [Butler and Russell, 2003, 18].

The subtraction method can be improved and the following topics seem to be promising:

– Improvement of the linearity criteria – some false linear segments detection can be avoided and faster algorithms are possible.

– Theoretical investigation of the transfer function in the non-linear segments where compensation from the temporary buffer takes place.

– Development of on-line method for the cases where PLI is variable in frequency and amplitude.

– Development of method in the case where the sampling rate is high (over-sampling).

5. ACKNOWLEDGEMENTS

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The paper has been reviewed by Professor Ph.D. Stefan Tabakov from Technical University – Sofia