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Noise Reduction Algorithm for Residual Gas Analyzer

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***Abstract*— A residual gas analyzer (RGA) is an instrument which, by ionizing the ambient gas under vacuum, enumerates the different atomic elements in the gas and measures their relative abundance. The data obtained from the RGA is contaminated by various noises, such as the power noises, measuring noise and etc. The various added noises degrade the ability to separate the atomic elements to represent the mass spectrum showing the composition ratio of the target gas. In this paper, we propose a novel noise reduction method, which is a digital signal processing technology required in developing the RGA, for reducing various noises added to the measurement data to improve the performance of the mass spectrum analysis. To reduce the additive noise in the measured data, the proposed method uses three steps of noise reduction according to the noise characteristics contained in the measurement data.**

Keywords*— *Residual Gas Analyzer; Mass Spectrum; Added Noise; Noise Reduction; Block Signal Processing

I. INTRODUCTION

A residual gas analyzer (RGA) is an instrument which, by ionizing the ambient gas in a low-pressure, enumerates the different atomic elements in the gas and measures their relative abundance. This measurement can be an extremely valuable since it allows one to know the chemical species involved in gas phase reactions and can help one to determine which reactions are most important [1]. The analysis of the gas is performed using a mass spectrometer, which identifies the atomic elements by separating the atoms, group of atoms, or molecules according to their mass to charge ratio (M/e). Mass spectrometers are classified on the basis of how the atomic mass separation is accomplished. Among various applications of the RGA, primary application is primarily to determine the residual gas in the vacuum system. Measuring a degree of vacuum by the composition analysis of this residual gas, a chemical reaction in the amount of up or system of the gas to flow into the vacuum system can be real-time Monitoring. Secondary application of the RGA is used as a leak detector of the vacuum system. The RGA, unlike a helium leak detector commonly used, without causing any effect on the vacuum system has the advantage that it can be used even without the helium gas [2]. Most of the semiconductor manufacturing process (Sputtering, CVD, PECVD, Plasma etching, etc.) is carried out in a vacuum system, Impurity gases such as oxygen, moisture, and hydrocarbon should be strictly regulated. The RGA is attacked to a semiconductor-producing chamber in order to use a number of process monitoring. The RGA is also used in various fields such as evolved gas analysis (EGA) on the analysis of the gas generated during the fermentation to control the fermentation process, and thermal analysis [3]. As shown in Fig. 1, the RGA can be largely divided into two parts. The first is a sensor part including the ionizer, a quadrupole mass filter, and an electron multiplier detector. And the second part is a control part which is composed of a 24V switching power supply, high voltage bias power supply for detector, RF/DC power supply for quadrupole mass filter, and MCU (main control unit) board for controlling the entire system, signal processing circuits, and monitoring system for display. The electron multiplier detector for the RGA is generally composed of a Faraday detector and electronic amplifier (the secondary electron multiplier) for measuring the ion current [4, 5].

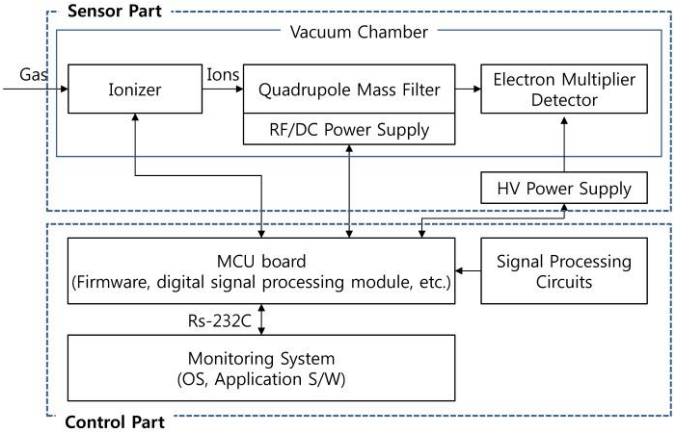

Fig. 1. Compositional diagram of residual gas analyzer.

The data obtained from the RGA is contaminated by various noises, such as the power noises occurring in different power for some units including the ionizer and the noises added to the electron multiplier detector. The various added noises degrade the ability to separate the atomic elements to represent the mass spectrum showing the composition ratio of the target gas. In developing the RGA, therefore, the securing of added noise removal technology is essential. However, it is very hard to remove these noises, because they are inevitably added noises which generated from the analog units (power supply, detector, pre-amp, etc.)[5].

This paper presents a novel noise reduction method, which is a digital signal processing technology required in developing the RGA, for reducing various noises added to the measurement data to improve the performance of the mass spectrum analysis. To reduce the additive noise in the measured data, the proposed method uses three steps of noise reduction according to the noise characteristics contained in the

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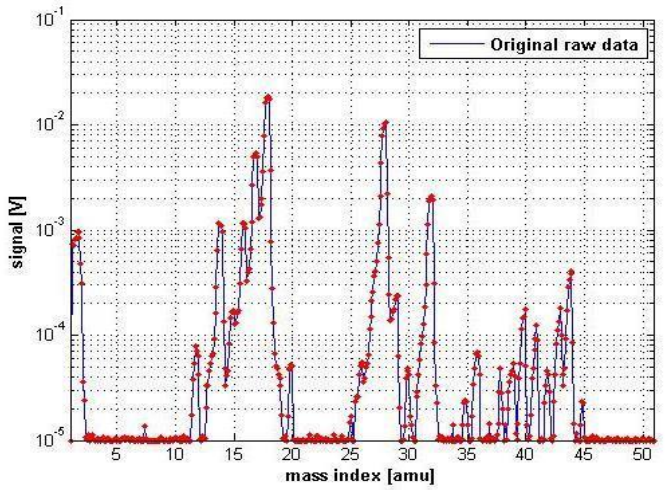

Fig. 2. Major peak of the mass spectrum, which of the residual gas measured by the RGA under development, are not clearly distinguished from each other

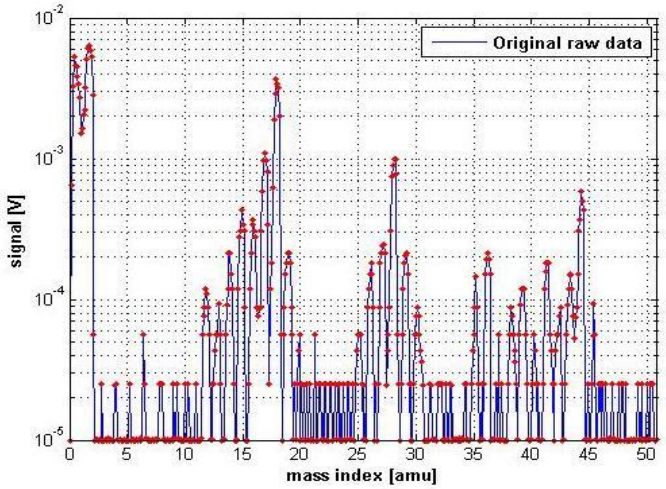

Fig. 3. Mass spectrum contaminated by a number of undesirable noises

measurement data. In order to evaluate the performance of the proposed method, computer simulations were carried out using a real measured data as the input.

II. Residual Gas Analyzer

An ion source in the RGA uses electron impact ion beam is ionized by collisions with neutral molecules or atoms as accelerating the thermal electrons are generated with the current flow in filament. The ion beam is subsequently passed into the quadrupole mass filter. It will very nicely pass through ions with a user chosen mass to charge ratio (*M*/*e*), but all the other ions get pushed aside into walls where they neutralize and become undetectable. The ions that are passed through this filter are detected as current at a Faraday detector. The ion current (abundance) detected by the Faraday detector is converted to a voltage signal using a pre-amp. The pre-amp gives a large amplification of the signal from ions and consequently is used to enhance the sensitivity of the RGA. However, the scan rate of the Faraday detector is decreased with increasing the gain of pre-amp. Therefore, the use of too high gain to amplify the small ion current measured by the Faraday detector, since it decreases the speed of analysis of the RGA, is not appropriate. By choosing a mass to charge ratio and making a measurement of the signal obtained, one can immediately find out the number of those molecules present in the ionizer region of the RGA. By sweeping through a whole range of *M*/*e* ratios, one can find a whole range of molecules that are present and begin to understand the full range of chemical components in the gas.

Since the RGA analyzes the composition of the volatile substance, the mass spectrometry range of 1 to 100(or 1 to 200) *amu* (atomic mass unit) and the 1 amu-resolution for separating the different peaks are sufficient specifications for the RGA. Fig. 2 and Fig. 3 show the mass spectrums (for mass range of 1 to 50 *amu*) of the residual gas measured by the RGA under development. The data used to plot the mass spectrum is raw data that is not any data processing is done (the data is original data source which obtained by the detector (the Faraday detector and pre-amp) and then which converted into digital data by the analog to digital converter). As you can see, major peaks of atoms or molecules in the mass spectrum of Fig. 2 are not clearly distinguished from each other. In contrast, the mass spectrum of Fig. 3 is contaminated by a number of undesirable noises. Therefore, in order to improve the analysis performance of the RGA, it is necessary to remove the added noises and to clearly separate the peaks of each amu.

III. The Proposed Method

In the RGA, after the ion signals corresponding to the atoms (or molecules) are measured by Faraday detector, they are converted to voltage signals by the pre-amp. To analyze mass spectrum using the microprocessor, the voltage signals is converted to a digital data by the ADC (analog to digital converter). When the digital-converted data obtained by the RGA defined as $s(n)$, it consists of the ion signal $v(n)$ corresponding to the atoms (or molecules) and the noise signal $u(n)$. We can express $s(n)$ as

$$s(n) = v(n) + u(n) \tag{1}$$

Where n is sample index (it means the time sequence). The noise signal, $u(n)$ consists of the additional noises caused by various electric devices such as the power supply, pre-amp, and the like. In developing the RGA, a sampling frequency used in the ADC is f_s *Hz*. Assuming that the power supply noise and the pre-amp noise of a frequency higher than the sampling frequency, these noises can be changed to a drift noises with low frequency by the aliasing. Also, white Gaussian noises are added to the obtained data in the process of signal detection and conversion. As shown in Fig. 3, since the sampling frequency is very lower than the frequencies of the drift noise and the white Gaussian noise, these noises can be shown like as impulsive noise and variations.

For the noise reduction, the proposed method uses a three-step denoising processes for a signal block that consists of the obtained signals. Consider the signal block that consists of the L+1 data samples, the signal block corresponding to the k-th amu is represented by

$$\mathbf{s}_k = [s(kL - \frac{L}{2}),\ s(kL - \frac{L}{2} + 1),\ \cdots,\ s(kL + \frac{L}{2})] \tag{2}$$

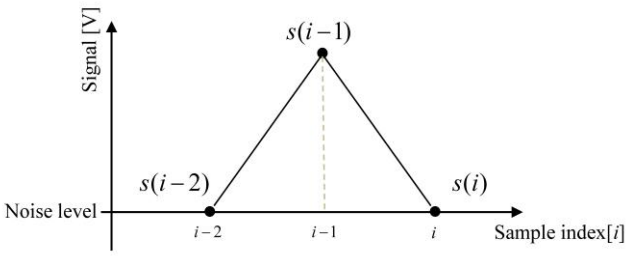

Fig. 4. Three consecutive samples including impulsive noise

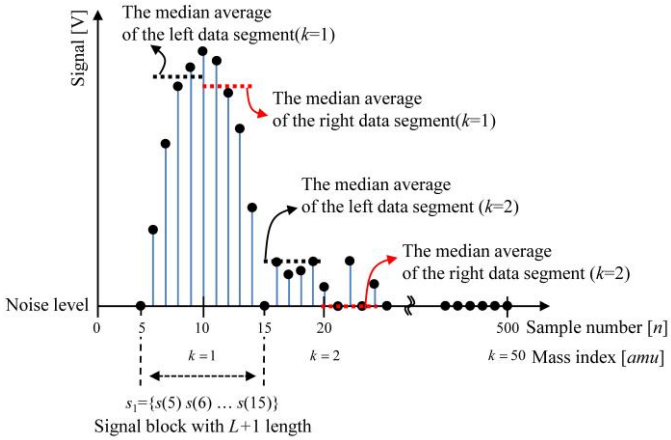

Fig. 5. Signal block with L=10 in the mass spectrum (0 ~ 50 amu)

where k is a positive integer and $0 \le k \le 50$.

In 1st denoising step, the impulsive noises are reduced for the signal block. First, the both ends of data samples in the signal block are set to noise level. The slops created by an impulsive noise data with its left/right data samples have the same size and opposite signs as shown in Fig. 4. In three consecutive samples, therefore, if the absolute value of sum of slops created by adjacent samples is equal to or close to zero, and if one of the both ends of the three samples is equal to the value of noise floor(noise level), the values of these three samples are all treated as noise level.

$$\begin{aligned} &if\ \{abs(Slope_L(i)+Slope_R(i)) \le \varepsilon\} \,\&\&\, \{s(i) \le noise\ level\} \\ &then\ \{s(i-2)\ \cdots\ s(i)\}\ are\ noises \end{aligned} \tag{3}$$

$$\begin{aligned} Slop_L &= s(i-1)-s(i-2), \\ Slop_R &= s(i)-s(i-1) \end{aligned} \tag{4}$$

where i is sample index and a positive integer (kL-L/2+2) $\le i \le$ (kL+L/2), the parameter ε is a very small positive value (in experiments, $\varepsilon \le 2\times10^{-5}$), abs(·) means an absolute value.

In the 2nd denoising step, noise reduction is performed by using the characteristics of the shape of a signal block measured per amu. Fig. 5 shows the signal blocks with L=10. If the added noise signal is negligible compared to the ion signal in the signal block, the signal block ($\mathbf{s}_k$) can be expected in the form of a substantially bilateral symmetry for each amu as shown in Fig. 5. For the 2nd denoising step, we define the following new data segments with L/2 length as

$$\mathbf{s}_{k,L} = [s(kL-\frac{L}{2}+1),\ s(kL-\frac{L}{2}+2),\ \cdots,\ s(kL)] \tag{5}$$

$$\mathbf{s}_{k,R} = [s(kL),\ s(kL+1),\ \cdots,\ s(kL+\frac{L}{2}-1)] \tag{6}$$

Where the central sample data in the block signal s(kL) is included in both left data segment ($\mathbf{s}_{k,L}$) and the right data segment ($\mathbf{s}_{k,R}$).

As shown in Fig. 5, In general, a median average value of each data segment for the ion signal block ($\mathbf{s}_{k=1}$), which is not a noise, divides the data samples of the data segments into two groups. If data samples of the signal block are not normal ion signals ($\mathbf{s}_{k=2}$), all the data can be up to or more than a median average in each data segment. If these results come from both left and right data segments, all the data of each data segment can be regarded as noise data.

$$\begin{aligned} &if\ \ (Case\ 1 = true)\,\&\&\,(Case\ 2 = true) \\ &then\ \{s(kL-\frac{L}{2}),\ s(kL-\frac{L}{2}+1),\ \cdots\ s(kL+\frac{L}{2})\} = noises\ level \end{aligned} \tag{7}$$

$$\begin{aligned} &Case\ 1: \forall \mathbf{s}_{k,L} \ge median(\mathbf{s}_{k,L})\ or\ \forall \mathbf{s}_{k,L} \le median(\mathbf{s}_{k,L}) \\ &Case\ 2: \forall \mathbf{s}_{k,R} \ge median(\mathbf{s}_{k,R})\ or\ \forall \mathbf{s}_{k,R} \le median(\mathbf{s}_{k,R}) \end{aligned} \tag{8}$$

where $\forall \mathbf{s}_{k,L}$ and $\forall \mathbf{s}_{k,L}$ are all the data of each data segment, and *median*(·) means that the median average value of the data segment.

In 3rd denoising step, noise reduction is performed using the ratio of the data having more than the noise level. The ratio is calculated from the remaining data except for both ends (right end and left end) of data samples in the signal block with L+1 length. If the number of data having greater value than the noise level is less than γ %(γ = 30 % used in experiments), all the data of signal block can be considered as noise data. In addition to the noise reduction in the proposed method, data re-arrange technique is used for improving the performance of expressing the mass spectrum to confirm the results of the residual gas composition analysis. The detailed procedure of the proposed method is shown in Fig. 6.

$$\begin{aligned} &if\ \ Ratio < 30\% \\ &then\ \{s(kL-\frac{L}{2}),\ s(kL-\frac{L}{2}+1),\ \cdots\ s(kL+\frac{L}{2})\} = noises\ level \end{aligned} \tag{9}$$

$$Ratio = \frac{Number\ of\ \mathbf{s}_k > noise\ level}{L-1} \times 100 \tag{10}$$

IV. SIMULATIONS

To evaluate the performance of the proposed noise reducing method, we carried out computer simulations with real measured signals as the input. The input signals are obtained from the RGA that is under development as shown in Fig. 1. In the RGA, Main parameters used for the quadrupole filter were

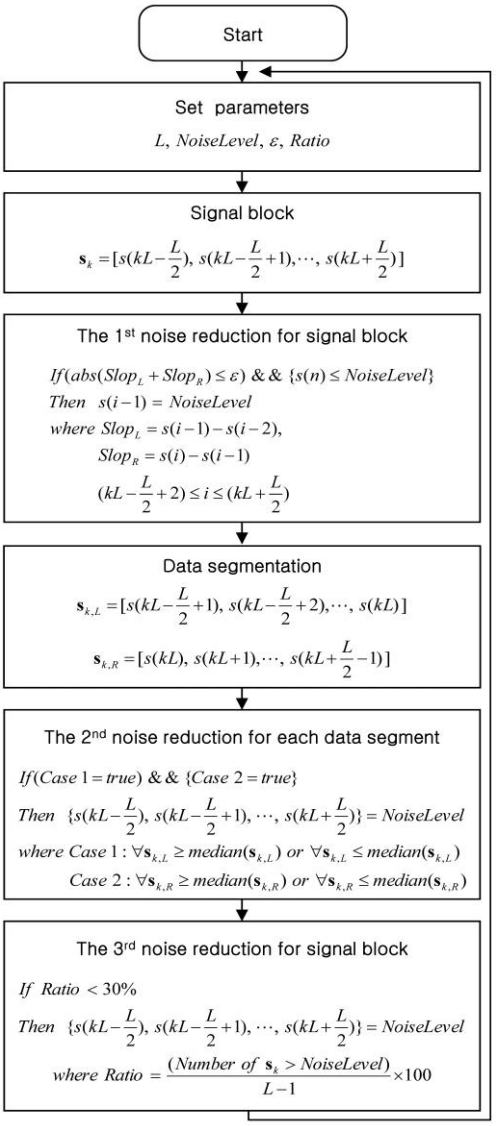

Fig. 6. Procedure of the proposed noise reducing method.

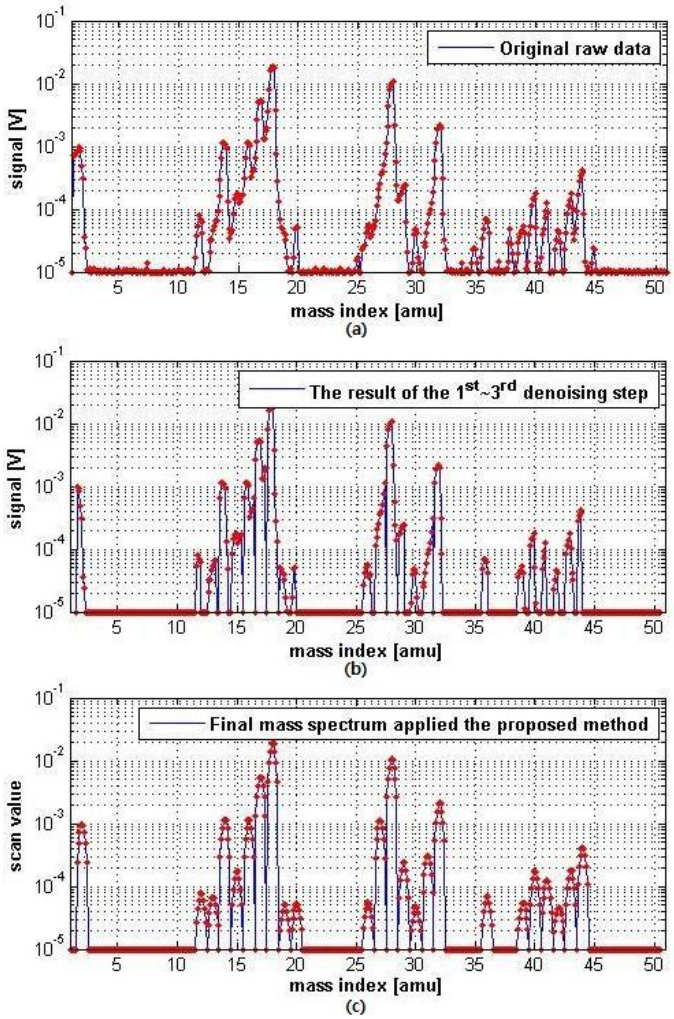

Fig. 7. Performance of the proposed method for the input signal of Fig. 2, (a) the original raw signal obtained form the RGA, (b) the result of the three denoising steps, (c) the improved performance in expression of the mass spectrum (The used parameters: L = 10, *NoiseLevel* = 1.0×10^{-5}, $\varepsilon \le 2\times10^{-5}$, γ = 30 %).

set to the electron energy is 70*eV*, the extraction is 20*eV*, and the focus is 10*eV*. Parameters for the detector were set to the pre-amp gain is 10^{-9}, the dwell time is 20μs. The scan range is 1 to 50 [*amu*] ($1 \le k \le 50$) for the mass spectrometry range. An output data rates (ODR) used for the digital data from the analog voltage signal obtained by the RGA is 10 samples per amu. The parameters used for the proposed denoising algorithm were set to the block length is L=10, the noise level is *NoiseLevel* = 1.0×10^{-5}, $\varepsilon \le 2\times10^{-5}$, the ratio is γ = 30 %.

Fig. 7 and Fig. 8 show the results of each denoising step for the mass spectrums which shown in Fig. 2 and Fig. 4 respectively. In Fig. 7(a), major peaks of atoms or molecules in the mass spectrum are not clearly distinguished from each other. Fig. 7(b) shows the performance of the proposed denoising algorithm with three steps. In Fig. 7 (b), the impulsive noises in mass index k = 7, 34 and 37 [*amu*], and the noises with insufficient non-noisy data samples in mass index k = 35, 37 and 38 [*amu*] have been removed by the 1st to 3rd denoising steps, respectively. Fig. 7(c) shows the result of the post-processing, which can help to distinguish the peaks of the atoms or molecules from each other by reshaping of the denoised data. From the results of the post-processing for improving the expression of the mass spectrum with the proposed denoising method, we can precisely confirm that there are major peaks at 18(H_2O), 28(N_2 & CO), 17(OH), and 32(O_2) [*amu*]. The next largest peak occur at 14(N), 16(O), 27(N_2+CO), and 2(H_2) along with peak 44(CO_2) [*amu*].

Fig. 8(a) shows the mass spectrum that contaminated by a number of undesirable noises. Fig. 8(b) shows the performance of the proposed denoising algorithm with three steps. In Fig. 8 (b), the noises, which appear throughout the entire mass index, have been removed by the three proposed denoising steps. As shown in Fig. 7(c), Fig. 8(c) shows a clear result of the mass spectrum.

V. CONCLUSIONS

This paper presents a novel noise reduction method and the post-processing method for improving the mass spectrum of the RGA under development. Three denoising steps to consider the characteristics of the noise signal were able to effectively remove the various noises. In addition to, the post-processing is

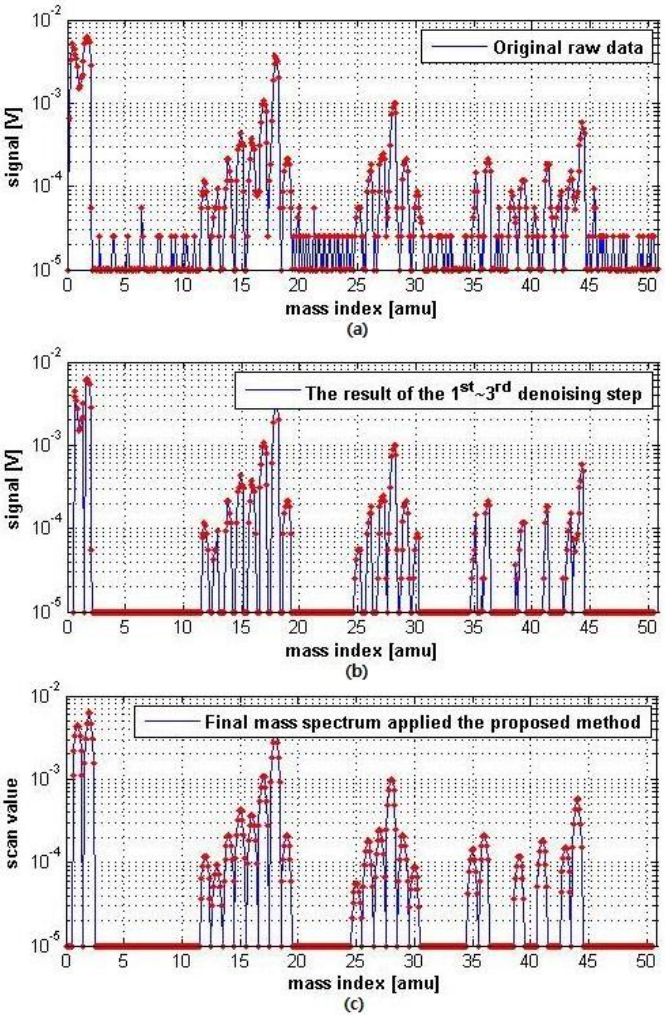

Fig. 8. Performance of the proposed method for the input signal of Fig. 3, (a) the original raw signal obtained form the RGA, (b) the result of the three denoising steps, (c) the improved performance in expression of the mass spectrum (The used parameters: L = 10, $NoiseLevel$ = 1.0×10^{-5}, $\varepsilon \leq 2\times10^{-5}$, γ = 30 %).

to be allowed to precisely distinguish between the peak of each atom or molecule by re-shaping the denoised data. Several simulation results have shown the good performance of the proposed method.

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VI. CONCLUSIONS

This paper presents a new mass concentration estimation algorithm for the particulate matter (PM_{10} and $PM_{2.5}$) monitoring system using the beta-ray absorption method. By combining the merits of the linear least squares function approximation (LLSFA) and the block signal processing (BSP), the proposed BSP-LLSFA method gives both excellent estimation of the mass concentration without processing delay and the method gives reduced computational complexity. The initial transient estimation performance of the proposed method can be improved by controlling the parameters used in BSP. Several simulation results have shown the good estimation performance of the proposed method.

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