Filter designs for removal of ECG baseline wander and power-line interference (December 2012)

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***Abstract*—Common artifacts that corrupt ECG signals are baseline wander and power-line interference. An ECG signal with these artifacts was preprocessed with filters to remove the artifacts. Filter designs and performances are discussed and evaluated. The filters include a low-pass FIR Equiripple filter to downsample the signal, two second-order IIR notch filters to remove the power-line interference and its harmonic, and a high-pass FIR Equiripple filter to remove the baseline wander. Alternative designs are also discussed and compared to the chosen designs.**

***Index Terms*—Baseline wander, power-line interference, notch filter.**

I. INTRODUCTION

THERE are many types of filters that can be used to modify the spectrum of a signal, eliminating unwanted components or amplifying desired components. Each filter type has different properties that make it well suited for particular types of filtering. Filters will be chosen by carefully considering how their advantages and disadvantages are relevant to the problem of removing baseline wander and power-line interference from an ECG signal.

II. SIGNAL TRUNCATION AND LOW-PASS FILTERING

The signal is flanked with unusable information on both ends, possibly due to the setup and removal of the recording equipment. Consequently, the signal was truncated from its original length of 162000, leaving samples 4930 through 150755, with length 145826. The cutoff locations were chosen by visual inspection to discard both the obviously corrupted signal, identified by its aperiodicity, as well as a single period of the signal on each end, identified by the "R" peak in the PQRST waveform, which is the most easily recognizable component in the waveform. To most accurately represent the signal, the first data point was chosen to be the "R" peak of the first period, and the last data point was chosen to be the sample immediately before the "R" peak of the last period. Fig. 1 and Fig. 2 respectively show the beginning and end of the signal.

The FFT of the signal shown in Fig. 3 shows the power-line interference and its harmonics at multiples of 50Hz. Furthermore, it allows verification by visual inspection that 95% of the signal energy has an upper limit of 100Hz. It follows that the original sampling frequency of 1000Hz is sufficient, but not necessary to model 95% of the signal's

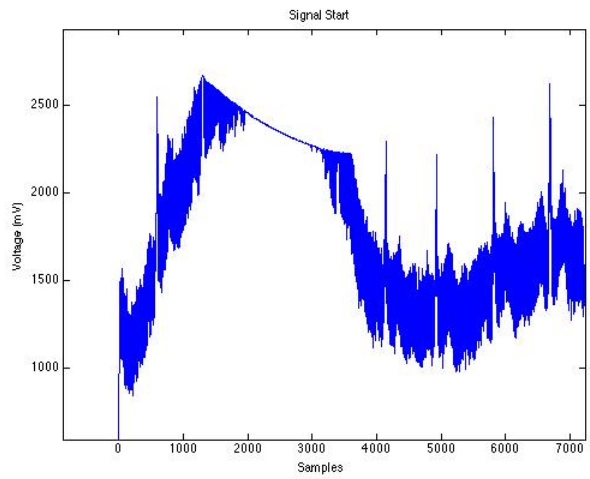


Figure 1

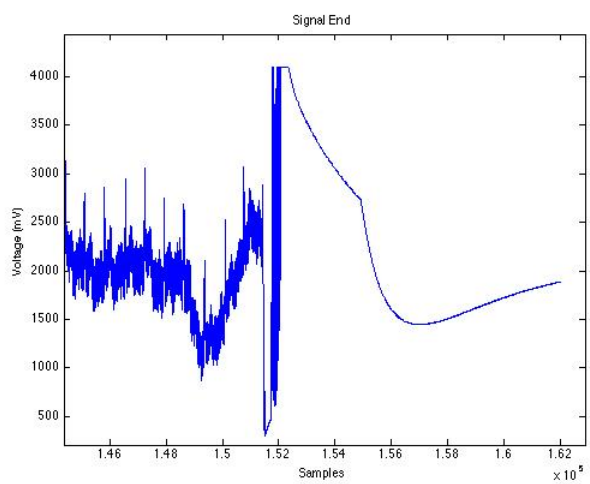
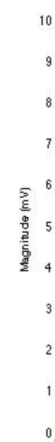


Figure 2



energy. The signal's spectrum can be band-limited as low as 100Hz without losing non-negligible information. Downsampling by 5 to 200Hz, for a Nyquist upper limit of 100Hz, will accomplish this. Since downsampling makes the spectrum periodic, the signal should be low-pass filtered to remove the high frequencies that could result in aliasing. However, if the passband cutoff frequency of the low-pass filter is at 100Hz to preserve 95% of the signal energy, and the stopband cutoff frequency is also at 100Hz to minimize the effect of aliasing, then the low-pass filter must have a zero-width transition region and infinite order.

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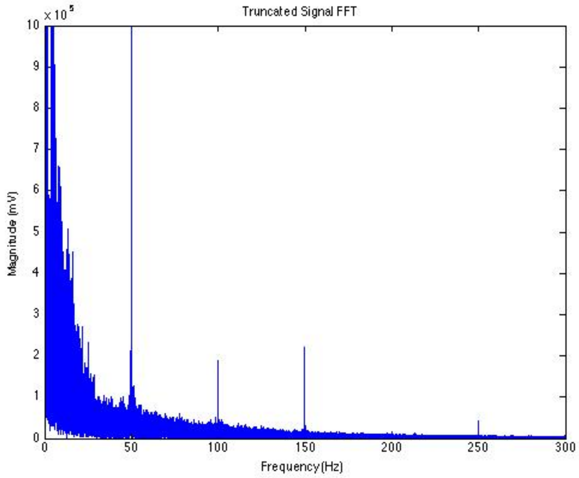

Figure 3

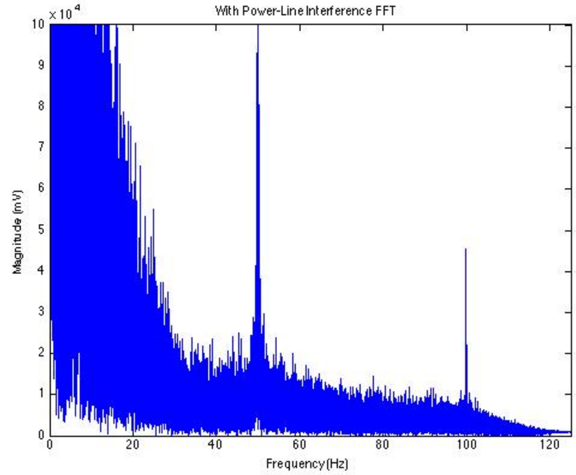

Figure 4

Since implementing an ideal low-pass filter is a poor design choice due to its impossibility, downsampling was chosen with the next highest factor: 4 instead of 5, making the sampling frequency 1000Hz/4 = 250Hz, the Nyquist frequency 250Hz/2 = 125Hz, the stopband cutoff frequency 125Hz, and the transition region 125Hz-100Hz=25Hz, allowing for a finite-order low-pass filter.

The constraint of an integer downsampling factor was imposed to avoid the computation involved with interpolating signal values at non-integer sample indices. The tradeoff in choosing the downsampling constraints is less computation with integer downsampling factor vs. lower bandwidth of the signal with non-integer downsampling factor between 4 and 5. A smaller signal bandwidth would make filter region bandwidths a larger portion of the spectrum, reducing filter order, but this benefit is minimal and is not justified with respect to the cost of processing a signal approximated via interpolation both due to interpolation errors and computational cost.

In designing the low-pass filter, linear phase, or constant group delay, was an important factor. The ECG signal represents a heartbeat, so maintaining signal integrity is critical to avoid misrepresenting the signal as an irregular heartbeat due to phase distortion. Accordingly, an FIR filter was chosen because constant group delay is guaranteed by imposing symmetry constraints on the impulse response. Of the possible FIR filters, a Parks-McClellan, or Equiripple, filter was selected to minimize the filter order given the filter parameters. The stopband was attenuated to 60dB, which corresponds to a factor of 1000, and the passband was attenuated to 0.01dB, which kept the gain between 0.999 and 1.001, which is important to avoid distorting the waveform. These conservative choices led to a filter order of 137, which requires more components to implement than would a lower order filter. However, since the filter order only changed linearly when the passband attenuation (in dB) was changed exponentially, it was determined that maintaining signal integrity and avoiding aliasing to the extent decided was worth the modest linear increase in computational complexity. Fig. 4 confirms that the low-pass filter operates as designed; in particular, the passband region appears unaffected, and the transition region between 100Hz and 125Hz tapers to a negligible magnitude response in the stopband. Subsequent downsampling did not noticeably affect the signal.

An alternative option as used in [1] would be to use a 4th order IIR Butterworth filter with cutoff frequency 100Hz. A plot of the group delay for this filter shows a non-linear increase from 4 to 7 samples at 0Hz to 100Hz. This design's advantage is the very small filter order, which would make the filter easy to implement. The effect of non-linear group delay may not be entirely detrimental since the group delay is rather small; however, having different regions of the spectrum moving by almost double that of other regions is a questionable choice for preserving a signal that cannot afford phase distortion. Lastly, the attenuation of this filter at the Nyquist frequency is only 10dB or a gain of 0.3, which may result in some aliasing. The high-order FIR filter was used rather than the low-order IIR filter due to prioritizing constant group delay; however, the alternative filter did appear to perform well in [1], so if implementation was a concern, the IIR filter may have been considered more strongly.

III. Power-Line Interference

The next step was chosen to be elimination of the power-line interference at 50Hz and its harmonic at 100Hz. The higher harmonics were eliminated by the low-pass filter. Since filter order is commutative with infinite precision arithmetic, the effect of filter order on the output is negligible. While constant group delay is an ideal property for filtering the ECG so that the phase isn't distorted, phase distortion may be permissible if the signal is attenuated enough at the frequencies where it occurs. The power-line interference resembles an impulse, which lends itself more to high attenuation at the center frequency that rapidly decreases as frequency deviates than to a filter with a constant attenuation over the bandwidth. This can be accomplished with a second-order IIR notch filter. Two

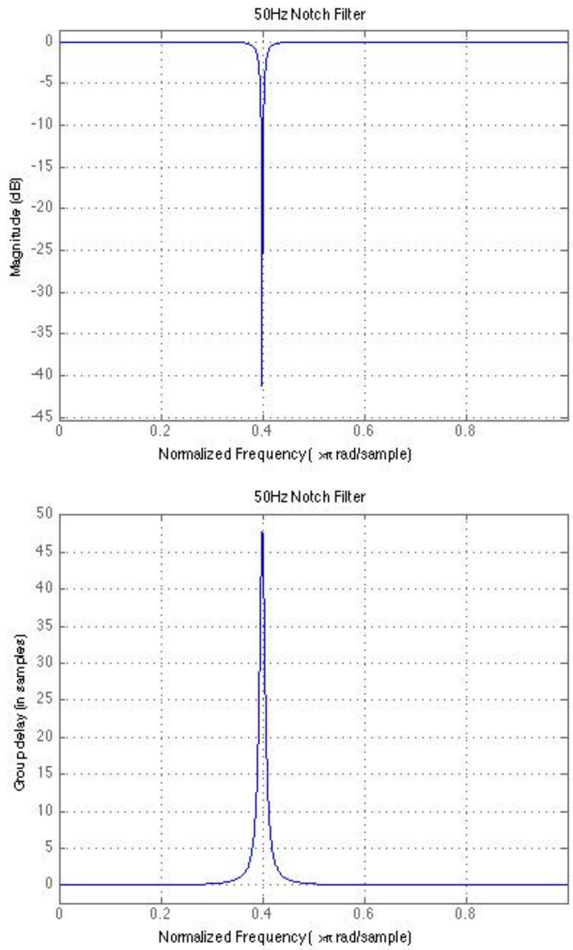

Figure 5

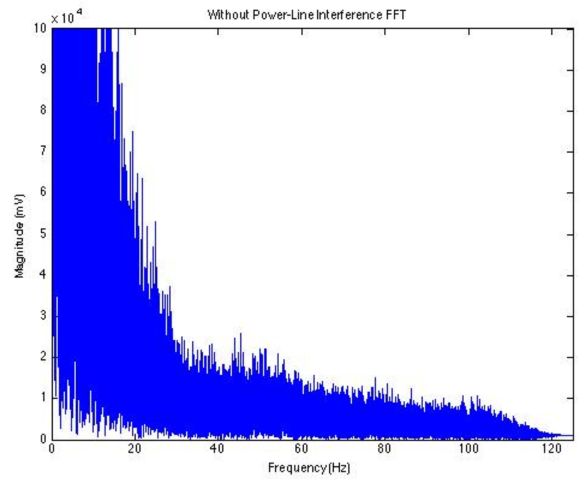

Figure 6

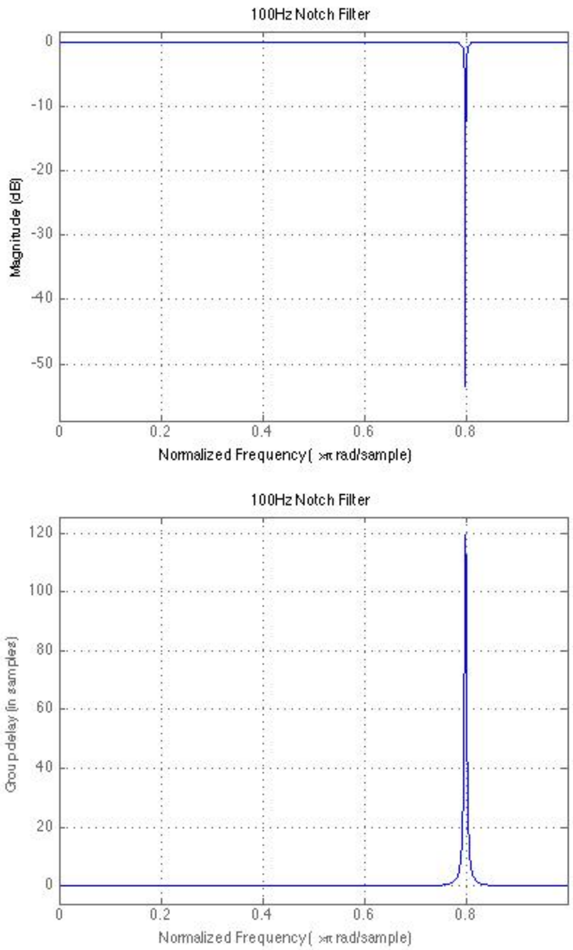

Figure 7

notch filters were used with center frequencies 49.95Hz and 99.9Hz and Quality factors 30 and 150, respectively. These frequencies were chosen because the power-line interference peaked there. The quality factors were made as high as possible to minimize phase distortion of neighboring frequencies that were not as attenuated, yet they needed to be low enough so that the bandwidth included enough of the power-line interference so that the filter could attenuate it. Fig. 5 and Fig. 6 confirm that the two notch filters remove the power-line interference and its harmonic. Fig. 7 shows the magnitude response of both filters as well as their group delays. It appears that the group delay approaches its peak more rapidly than the magnitude response is attenuated. This may result in neighboring frequencies with non-negligible group delay; however, those frequencies will nonetheless have attenuated magnitudes, and the effect on the signal will mostly distort the noise, rather than the signal.

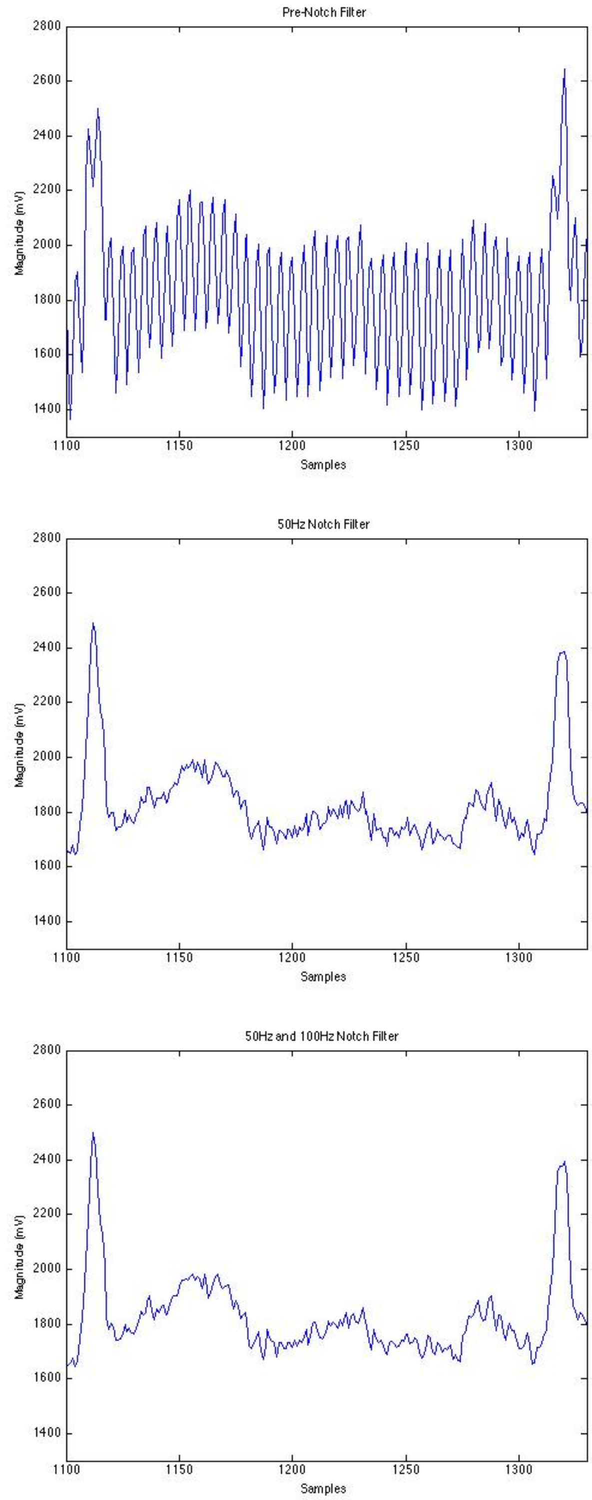

Figure 8

The effect of the notch filters on the signal in the time-domain is presented in Fig. 8. It is evident that the 50Hz notch filter removes the visible 50Hz power-line interference by comparing the signal waveform before and after. However, the effect of the 100Hz notch filter is almost unnoticeable. This is reasonable because harmonics have smaller magnitude responses, as Fig. 5 shows, thus their removal is less significant. Nonetheless, the presence of the 100Hz notch filter is still justified because the 100Hz power-line harmonic is noticeable in the frequency domain, and because the computational cost of a second-order IIR filter is very small compared to the rest of the filters used in this paper.

The notch filters were designed with a zero on the unit circle at the specified frequency and a pole at the same frequency, inside the unit circle. The effect of the zero is to zero the gain at the resonant frequency and to attenuate the magnitude response at nearby frequencies. The pole is close to the zero so that at frequencies farther from the resonant frequency, the pole and zero almost cancel each other and the gain approximates 1. Accordingly, the closer the pole is to the zero, the higher the quality factor. Furthermore, the causal filter is stable since the pole is inside the unit circle. This configuration occurs at both the positive and negative resonant frequency, making the filter second order; the presence of poles makes it IIR. The resonant frequency must be specified with respect to the sampling or Nyquist frequency, where the Nyquist frequency corresponds to π, because pole and zero placement in the complex plane is limited to $\omega=\pm\pi$.

IV. BASELINE WANDER

The baseline wander is responsible for the offset of the signal, as well as for other waveform distortions from low frequencies. It makes it difficult to compare heartbeats that have different offsets, which warrants its removal with a high-pass filter. Since the heartbeat in this signal is around 70 beats per minute, or 1.17Hz, the passband cutoff frequency cannot be greater than this value, so a conservative choice of 1.15Hz was determined. Any higher choices caused intrinsic components of the heartbeat waveform to be attenuated to unacceptable levels. To decrease the filter order, the transition band was made as large as possible; since there was no constraint on the lower end, the transition band was extended all the way to 0Hz[1]. With the passband attenuation set to a maximum of 1dB, the stopband attenuation was increased until there were diminishing returns on the signal mean squared error, indicating enough of the baseline wander was removed. The stopband attenuation was not increased beyond this point of 30dB because the filter order would have been increased and the benefit of increased baseline attenuation was not worth the increased computational cost of a higher order filter, despite the non-negligible but attenuated impulse of the baseline spectrum. The filter was implemented with an FIR Equiripple filter to avoid phase distortion and minimize the

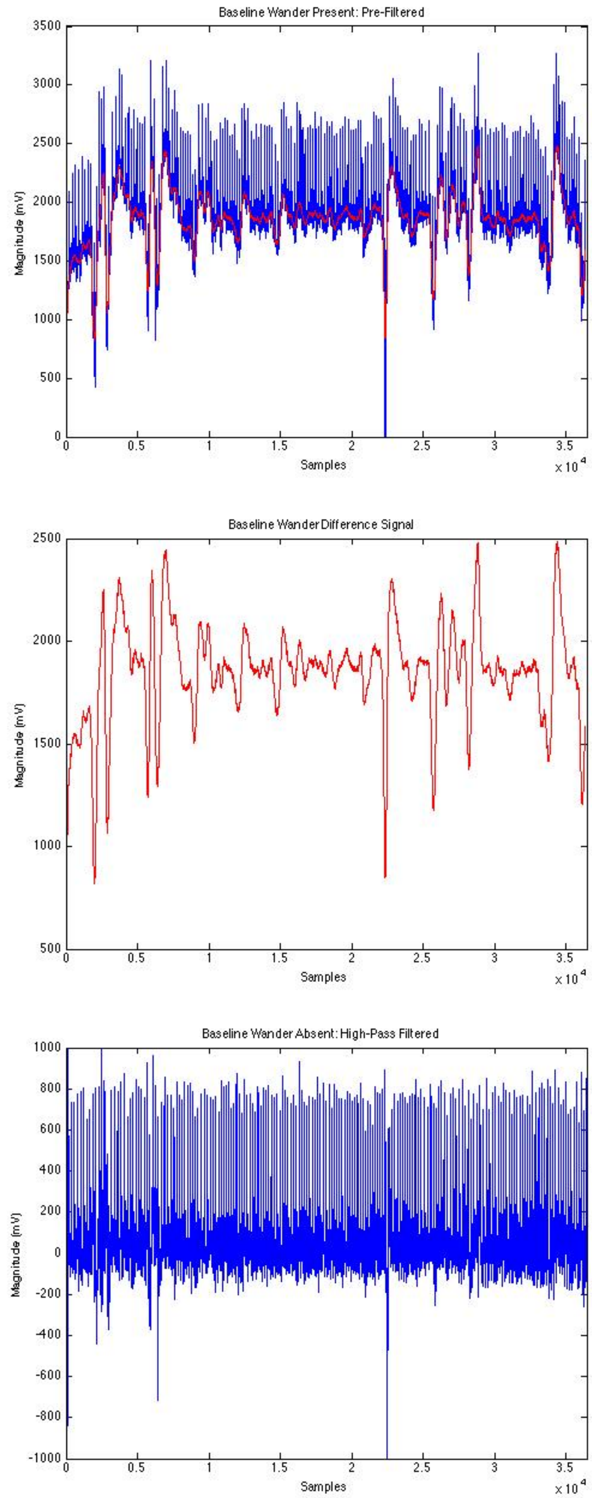

Figure 9

[1] The lower bound of 95% signal energy is 0.5Hz and should separate the stopband and transition band, increasing the filter order. This should not significantly affect the analysis.

filter order (to 218), given the parameters. All the poles were located at the origin, and the zeroes were located in inside and outside the unit circle in complex conjugate reciprocal pairs. At high frequencies the effect of the zeroes can be approximated by their centroid near the origin, which almost cancels the poles, approximating a gain of 1. At low frequencies, the zeroes are closer to the unit circle and attenuate the magnitude response. Fig. 9 shows the effect of removing the baseline wander from the signal, as well as the difference signal between the input signal and the delayed output signal, which represents the baseline wander and possibly respiration. For clarity, the baseline wander has been superimposed on the input signal to show how subtracting it (in the form of a high-pass filtering) could lead to the output signal. There are a few regions where increased baseline removal would improve the output signal resemblance to a heartbeat waveform; however the order required to achieve this is impractical for computation in a reasonable time-frame.

An alternative filter design to remove the baseline wander is an IIR notch filter, which would dramatically reduce the filter order, but at the cost of potential phase distortion. However, like in the power-interference filters, it's possible that any frequencies exhibiting phase distortion may have magnitude responses that are attenuated enough that phase distortion becomes negligible. One reason that this is not a common solution for removing baseline wander but is common for removing power-line interference and harmonics may be that the phase distortion of neighboring frequencies at the baseband occurs where the heartbeat signal of 70bpm is greatest. The risk of signal distortion at 50Hz and 100Hz may be negligible, but unacceptable at 0Hz.

V. Quantization Effects

The input signal is quantized to 12 bits, so the output should also be represented with 12 bits. If the filters are implemented with finite-precision arithmetic, the signal can be represented with 12 bits at every stage during preprocessing. The advantage is decreased number of components required for computing; however, the disadvantage is the introduction of quantization error. The filter poles may have to be shifted to the nearest allowable locations, which could affect the properties of the filter such as resonant or cutoff frequencies, and magnitude response. One approach would be to simply see if the new output meets the design specifications, and re-design if necessary. Another option could be to increase the number of bits during the intermediate stages, and round or truncate the signal back to 12 bits at the end. Furthermore, there are many different configurations for implementing a second-order IIR filter [2], so consideration would also have to be given to the propagation of error.

VI. Conclusion

The PQRST waveform is visible after power-line interference is removed. Baseline wander removal is also successful, yet there is much room for improvement, as the final signal is still noisy. Many more sophisticated approaches have been published and may help direct future studies.

References

1. J. A. Van Alste, W. Van Eck, and O.E. Herrmann, “ECG Baseline Wander Reduction Using Linear Phase Filters,” in *Computers and Biomedical Research* 19, 417-427 (1986).
2. K. Hirano, S. Nishimura, and S. K. Mitra, “Design of Digital Notch Filters,” *IEEE Transactions on Communications*, Vol. COM-22, No. 7, July 1974.