Biosignal filtering and artifact rejection

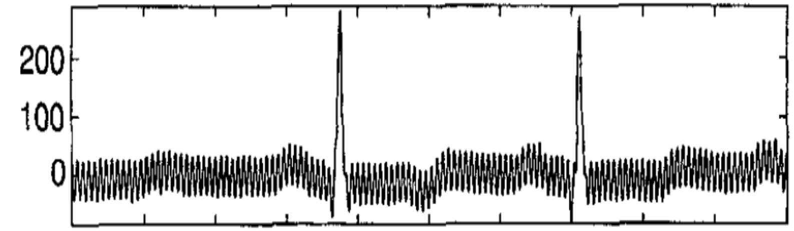
Biosignal processing I, 521273S
Autumn 2019

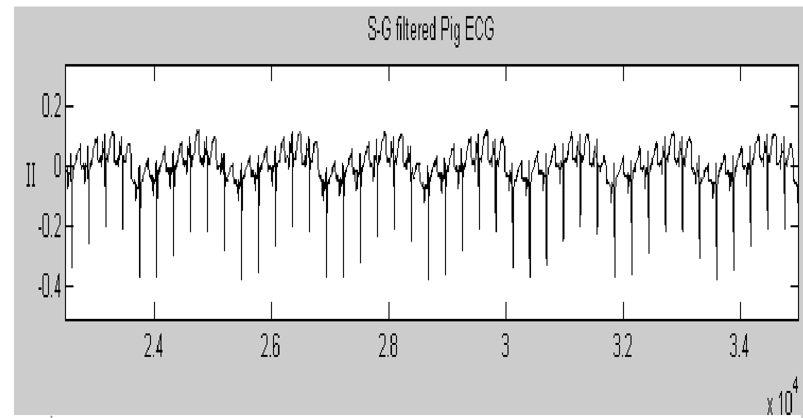
Motivation

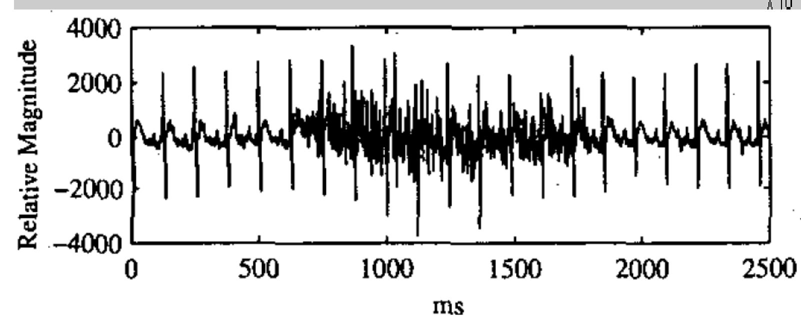
1) Artifact removal

- power line
- non-stationarity due to baseline variation
- muscle or eye movement artifacts in EEG or ECG

- Solution?: epoch rejection due to artifacts

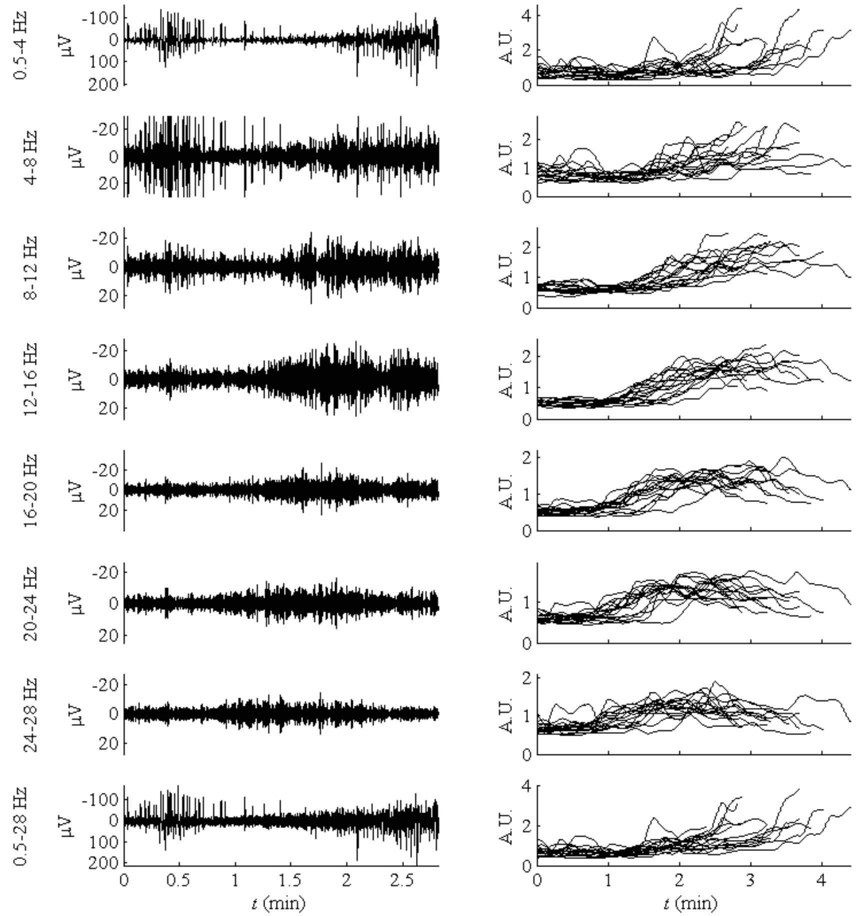


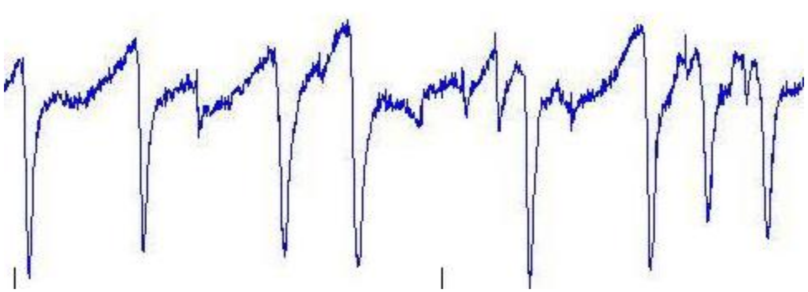




2) Enhancement of useful information

- bandpass filtering
- finding certain signal waveforms such as eye blinks from EEG or QRS complexes from ECG
- smoothing for illustrative purposes





A few words on an example signal: ECG

ECG:Electrocardiogram

- Electrical potential changes due to contractile activity of the heart
- Measured usually by standard 12-lead system
  - With four limb electrodes and six chest electrodes
- Common ECG-applications are
  - stationary ECG
  - Holter-monitoring
  - stress-ECG (exercise testing)
  - telemedicine applications
  - heart rate monitors
- Invasive intrumentation:
  - heart pacemakers
  - arrhythmia-pacemakers

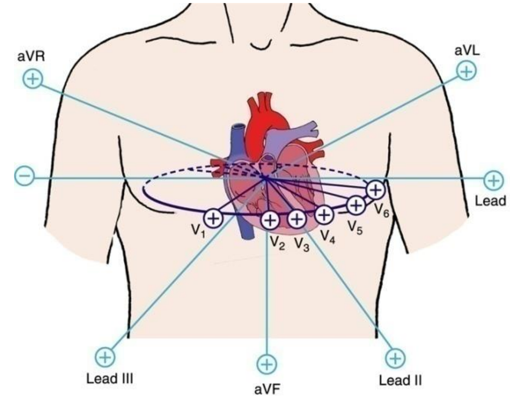
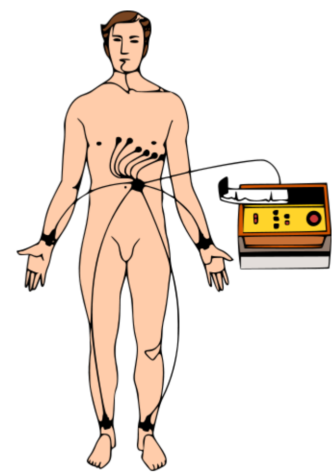
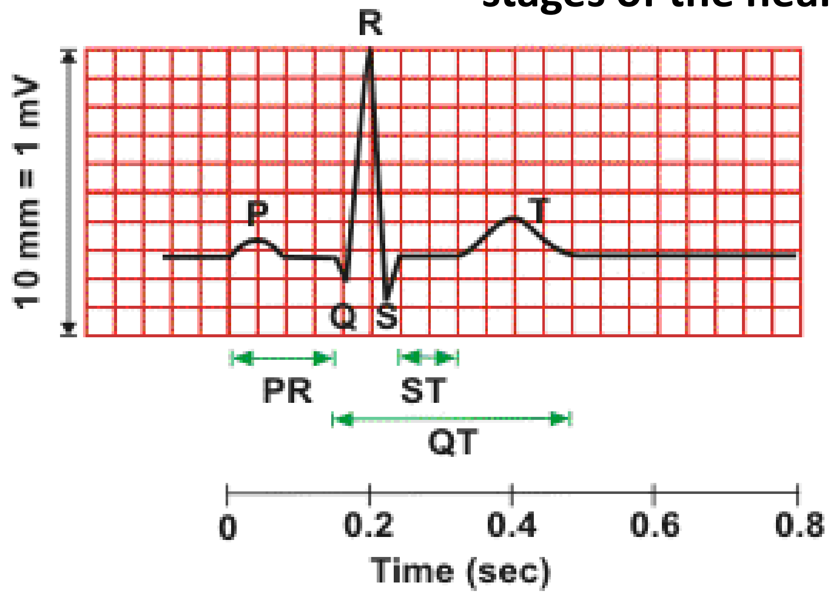


Figure 17-42 Electrocardiographic views of the heart.



ECG structure

Contraction and relaxation stages of the heart



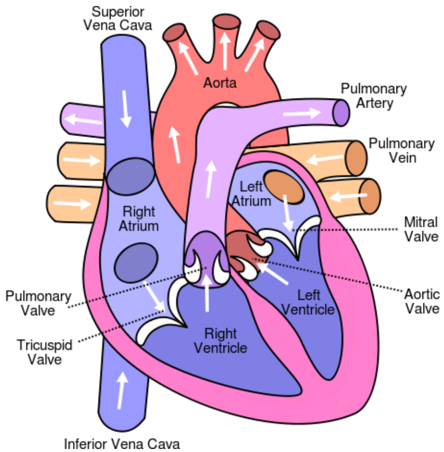
E.g. Feature analysis

Automatic detection of different segments and waves (amplitudes, intervals)

P wave (0.08 - 0.10 s) QRS (0.06 - 0.10 s)

P-R interval (0.12 - 0.20 s) Q-T_C interval ($\leq$ 0.44 s)*

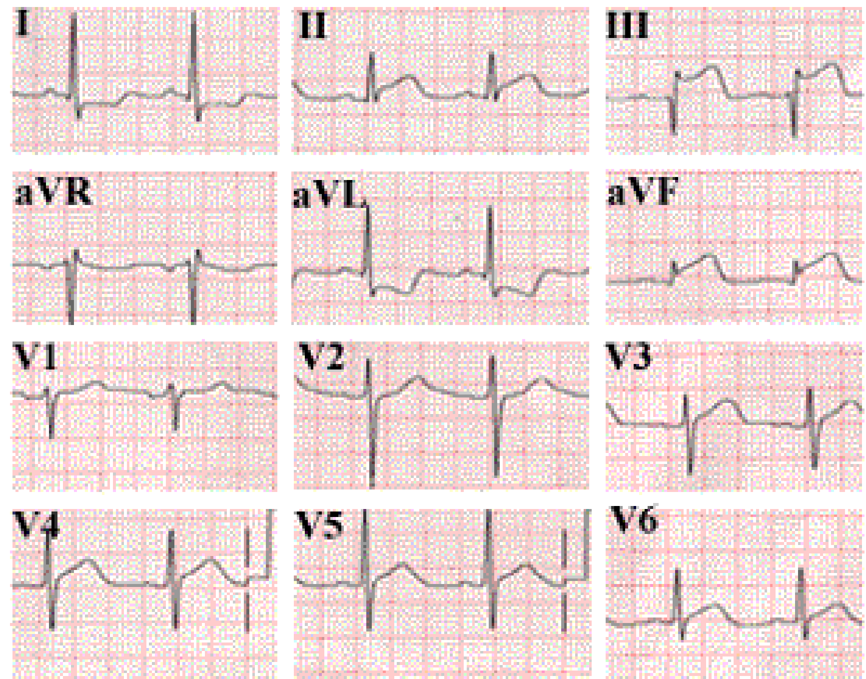
$$^{*}QT_C = QT/\sqrt{RR}$$



Systemic vs. pulmonary circulation

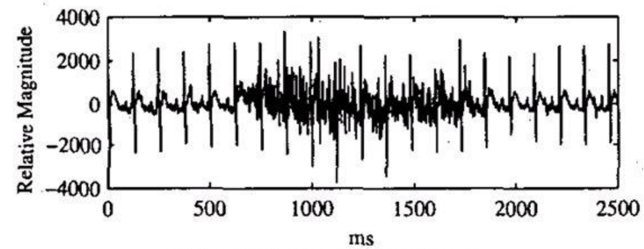
12-lead ECG

- ECG analysis focus:
  - QRS complex detection
  - feature analysis
  - classification of arrhythmias
  - ECG signal compression
  - Heart rate variability (HRV) analysis



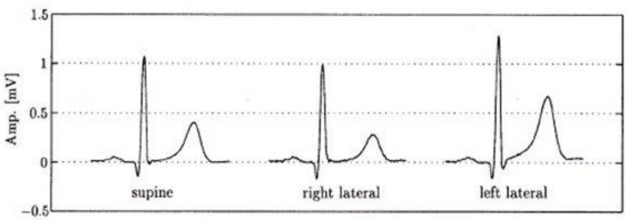
Noise in ECG

Distortion caused by electromyogram:

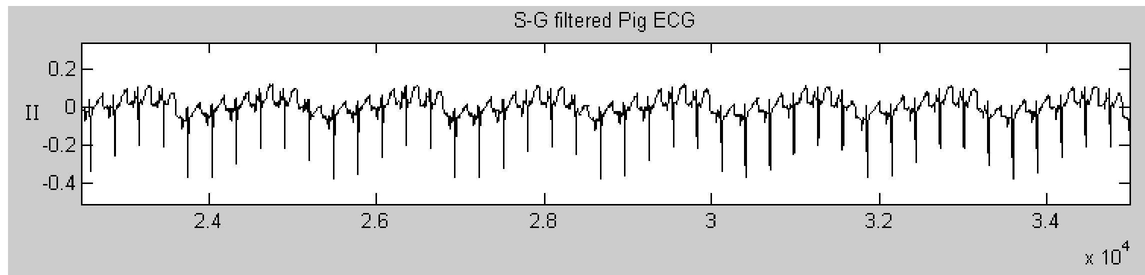


Recorded ECG corrupted by EMG noise.

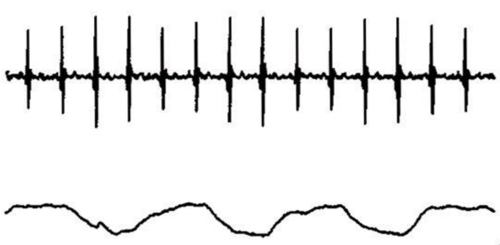
Effect of body position on ECG:



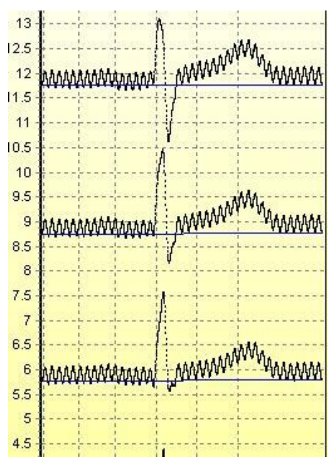
Beat morphologies for three different body positions.



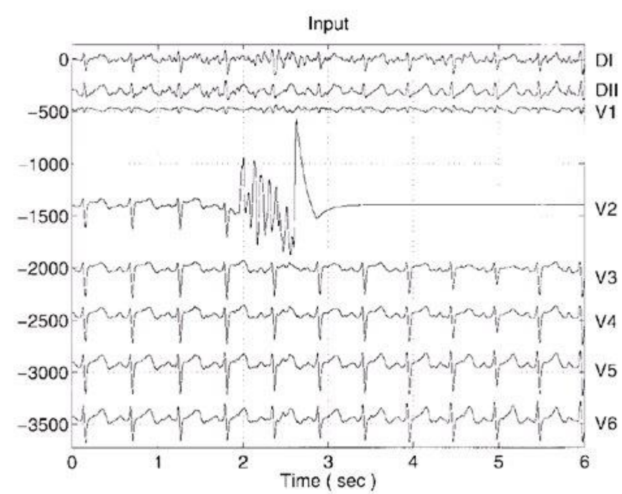
Respiration-induced ECG modulation:



ECG (upper trace) and respiration measured by a pneumatic respiration transducer placed around chest (lower trace).



Channel loss:



Complete loss of channel V_2 during recording.

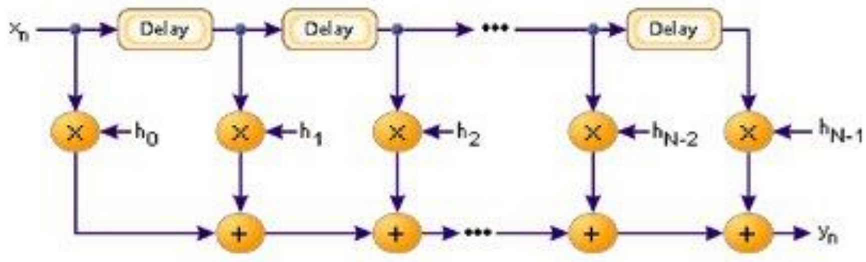


Figure 2. The logical structure of an FIR filter

Basic filtering techniques

FIR filters

- **F**inite **I**mpulse **R**esponse (FIR) filter
  - Stable
  - Simple to implement
  - Linear phase response
    - Symmetrical impulse response
    - All frequencies have the same amount of delay – no phase distortion

$$y(n) = \sum_{k=0}^{N-1} h(k)x(n-k)$$

$$H(z) = \sum_{k=0}^{N-1} h(k)z^{-k}$$

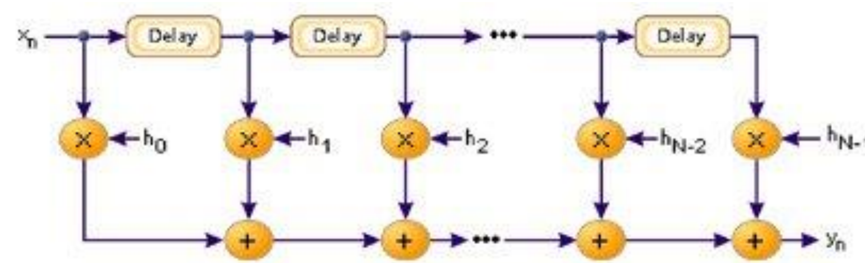
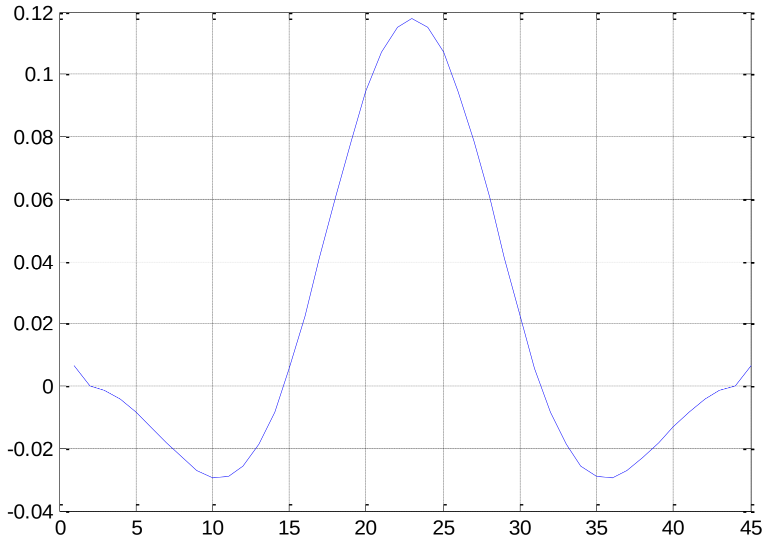
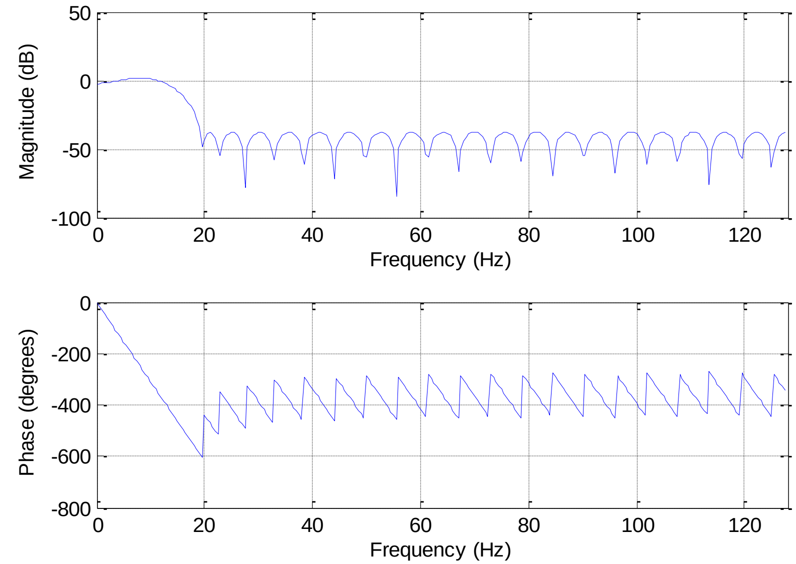


Figure 2. The logical structure of an FIR filter

Source: http://www.netrino.com/Publications/Glossary/Filters.php

FIR





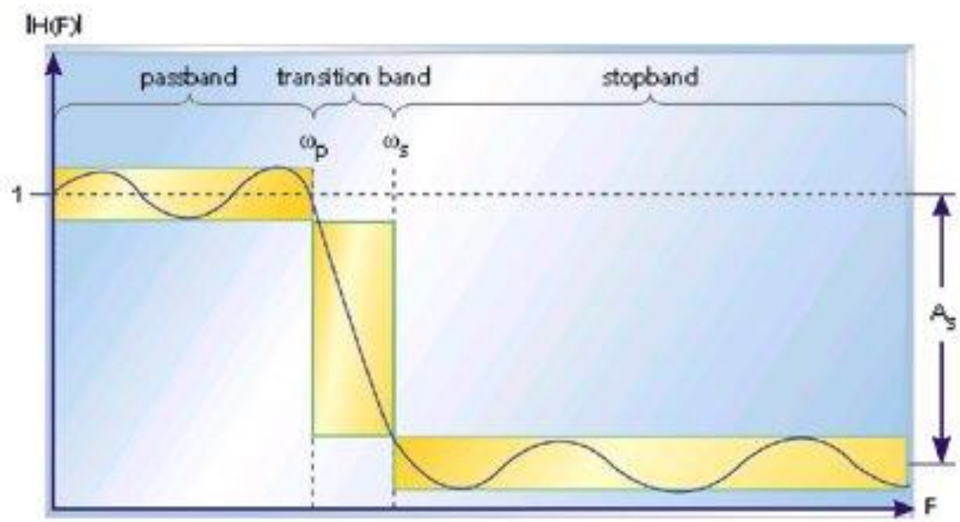


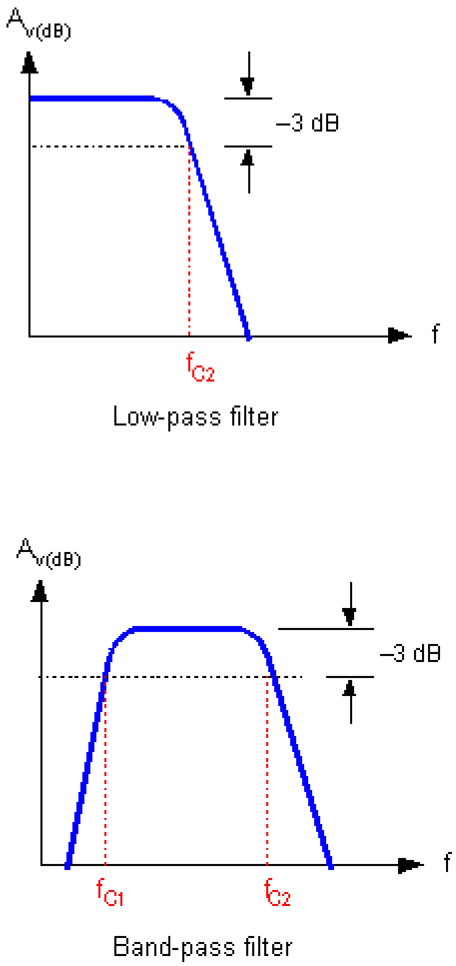
Figure 1. The response of a lowpass filter to various input frequencies

Lowpass filter, order 44 (N=45), positive symmetry.
fs=256 Hz, Fp=13 Hz, Fs=19 Hz, Rp=4 dB, As=38 dB

Filter characteristics:

sampling frequency fs, passband Fp, stopband Fs, ripple Rp, attenuation As

Filter types by spectral characteristics



Smoothing: averaging filter

- Average of a sliding window of size N samples
  - FIR filter

$$y(n) = \frac{1}{N}\sum_{k=0}^{N-1} x(n-k) = \frac{1}{N}[x(n-0)+x(n-1)+\ldots+x(n-N+1)]$$

$$= \frac{1}{N}x(n-0)+\frac{1}{N}x(n-1)+\ldots+\frac{1}{N}x(n-N+1)$$

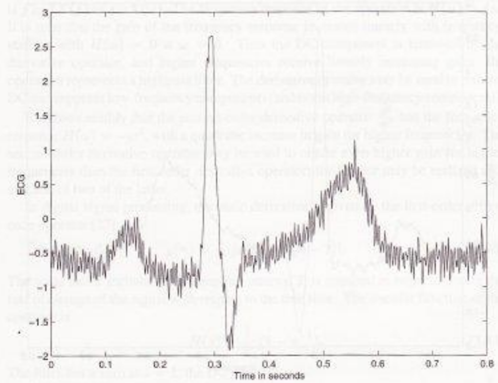


Figure 3.20 ECG signal with high-frequency noise; $f_s = 1{,}000\ Hz$.

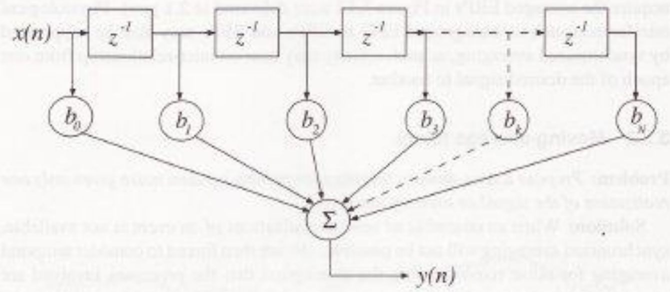


Figure 3.15 Signal-flow diagram of a moving-average filter of order N. Each block with the symbol z^{-1} represents a delay of one sample, and serves as a memory unit for the corresponding signal sample value.

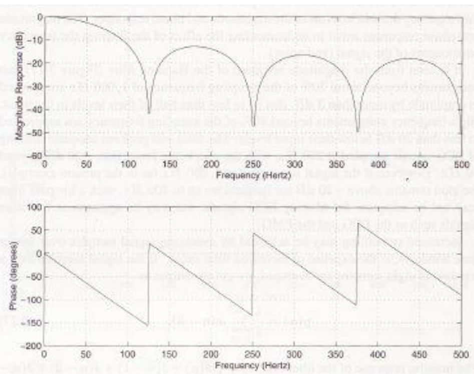


Figure 3.18 Magnitude and phase responses of the 8-point moving-average (smoothing) filter.

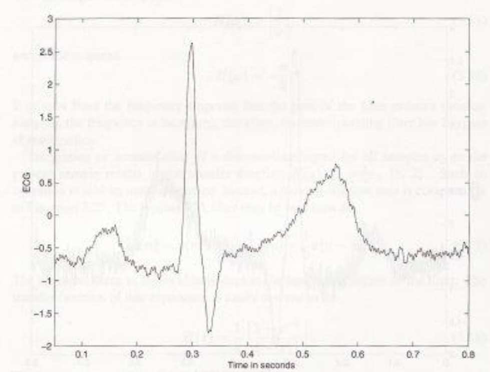


Figure 3.21 The ECG signal with high-frequency noise in Figure 3.20 after filtering by the 8-point MA filter shown in Figure 3.18.

Smoothing: Hanning filter

$$H(z) = \frac{1}{4}[1 + 2z^{-1} + z^{-2}]$$

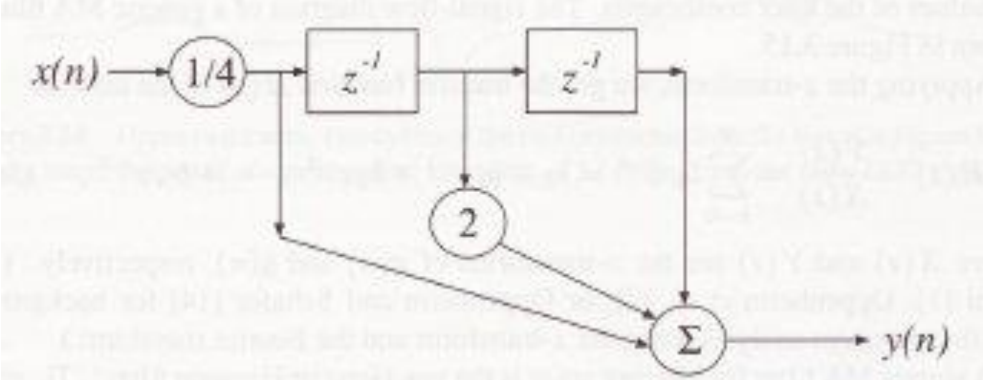


Figure 3.16 Signal-flow diagram of the Hanning filter.

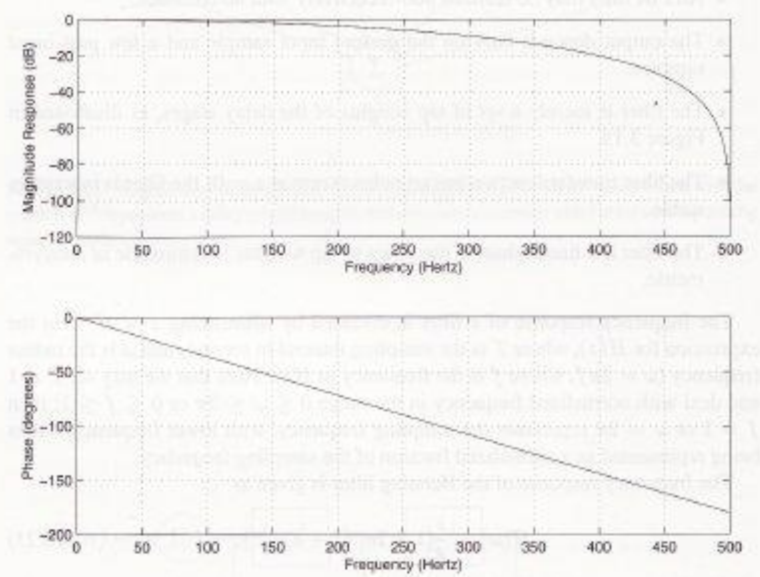


Figure 3.17 Magnitude and phase responses of the Hanning (smoothing) filter.

IIR filters

- **I**nfinite **I**mpulse **R**esponse (IIR) filters
  - Feedback system
  - Normally fewer coefficients that with FIR
  - Used for sharp cut-off (notch filters for example)
  - Can become unstable or performance degrade if not designed with care
  - Pole-zero diagram
  - Nonlinear phase characteristics causes phase distortion altering harmonic relationships – frequency components have different time delays (often undesirable)
    - The wave shapes are distorted!

$$y(n) = \sum_{k=0}^{\infty} h(k)x(n-k) = \sum_{k=0}^{N} b_k x(n-k) - \sum_{k=1}^{M} a_k y(n-k)$$

$$H(z) = \frac{b_0 + b_1 z^{-1} + \ldots + b_N z^{-N}}{1 + a_1 z^{-1} + \ldots + a_M z^{-M}} = \frac{\sum_{k=0}^{N} b_k z^{-k}}{1 + \sum_{k=1}^{M} a_k z^{-k}}$$

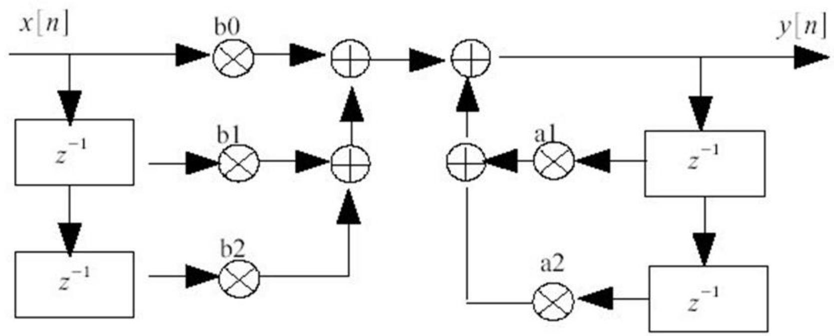


Figure 6: Network diagram for an IIR filter having two poles and two zeros.

Source: http://www.triplecorrelation.com/courses/fundsp/iiroverview.pdf

Smoothing: Butterworth lowpass filtering

Butterworth lowpass filter

- Select suitable order and cutoff frequency
- Maximally flat magnitude filter

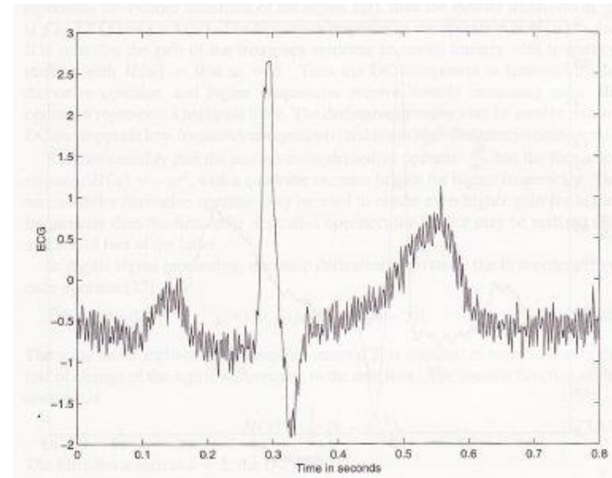


Figure 3.20 ECG signal with high-frequency noise; $f_s = 1{,}000\ Hz$.

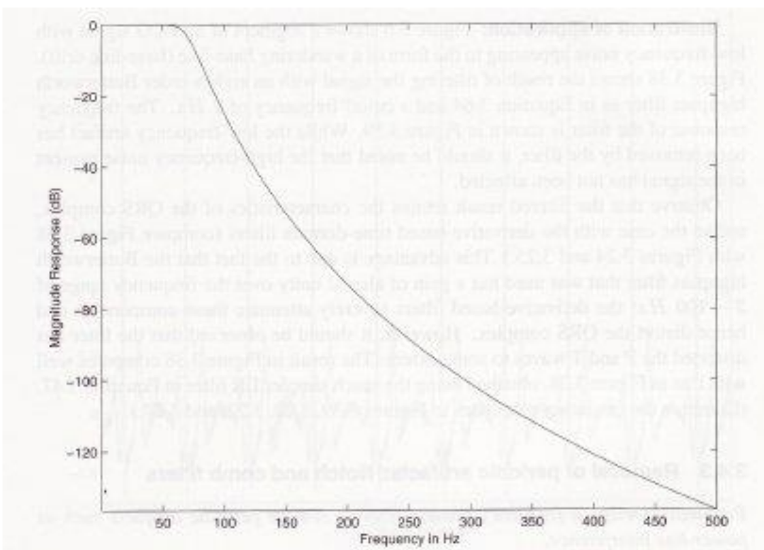


Figure 3.37 Frequency response of the eighth-order Butterworth lowpass filter with cutoff frequency = $f_c = 70\ Hz$ and $f_s = 1{,}000\ Hz$.

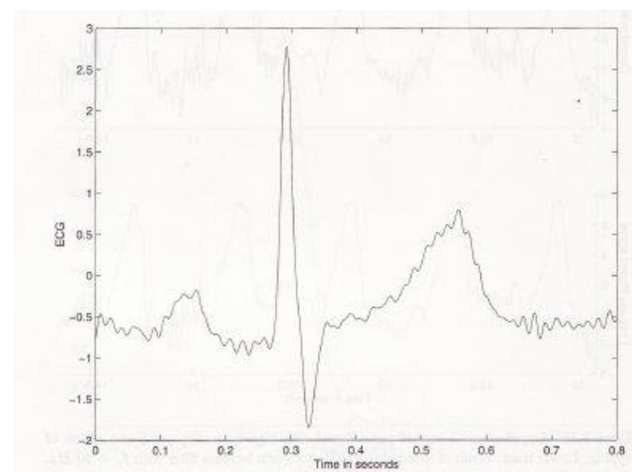


Figure 3.36 Result of frequency-domain filtering of the noisy ECG signal in Figure 3.20 with an eighth-order Butterworth lowpass filter with cutoff frequency = $70\ Hz$.

Notch/comb filter

- Often used for 50/60 Hz power line artifact filtering
- Narrow stop-band in basic and harmonic frequencies
- Be careful with the aliased harmonics
- Can be implemented as FIR or IIR

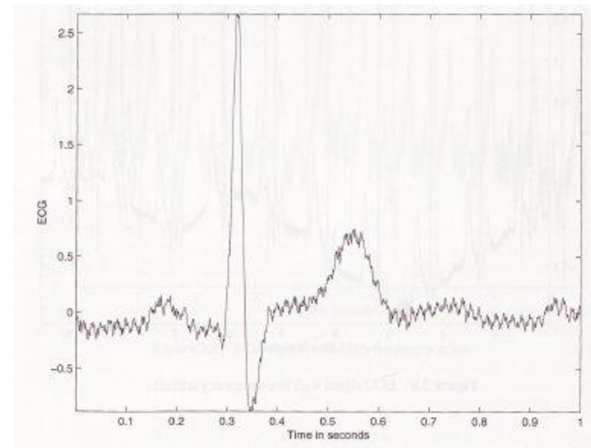


Figure 3.7 ECG signal with power-line (60 Hz) interference.

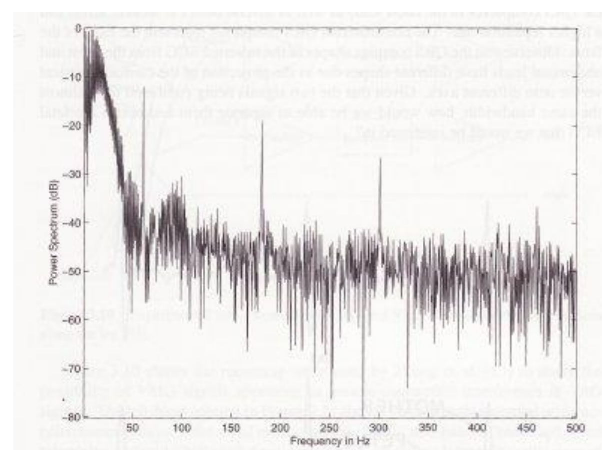
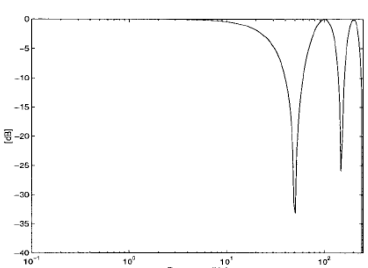


Figure 3.8 Power spectrum of the ECG signal in Figure 3.7 with power-line interference. The spectrum illustrates peaks at the fundamental frequency of 60 Hz as well as the third and fifth harmonics at 180 Hz and 300 Hz, respectively.



$$y(t) = x(t) - 2 \cdot x(t-16) + x(t-32) - 2 \cdot y(t-8) - y(t-16).$$

Ruha et al. (1997)

Notch/comb filter

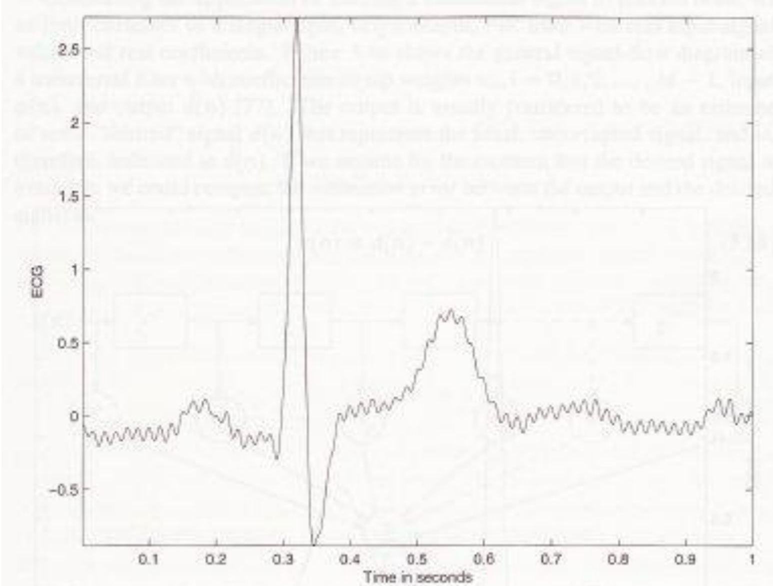


Figure 3.44 ECG signal with 60 Hz interference.

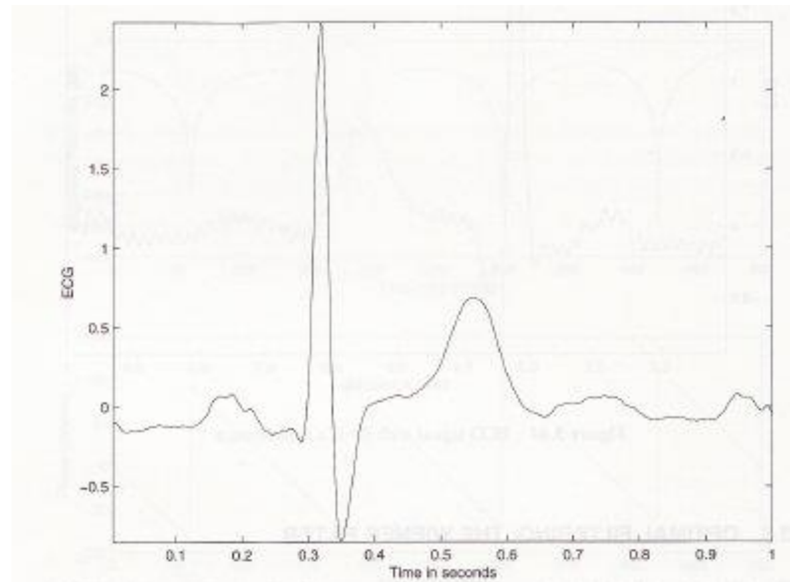


Figure 3.45 The ECG signal in Figure 3.44 after filtering with the 60 Hz notch filter shown in Figures 3.40 and 3.41.

Original signal

Filtering result

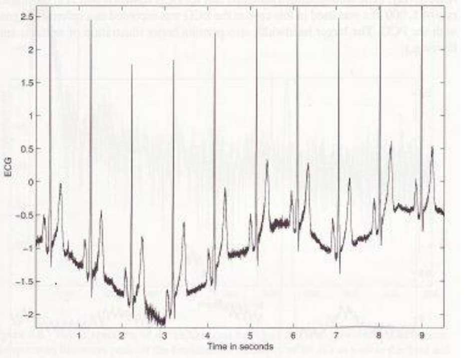


Figure 3.6 ECG signal with low-frequency artifact.

Trend removal

Trend removal - detrending

- The signal baseline may vary due to, e.g. non-perfect electrode attachment
  - The baseline wondering may disturb analysis of signal properties
  - It is thus favorable to remove the baseline as well if necessary for the application

- High-pass filtering
  - time-domain: difference filter
  - frequency-domain: DFT (discrete Fourier transform)
- Trend removal with other methods
  - Savitzky-Golay filter

Difference filtering, version 1

First-order difference operator:
T=sampling interval

$$y(n) = \frac{1}{T}[x(n) - x(n-1)]$$

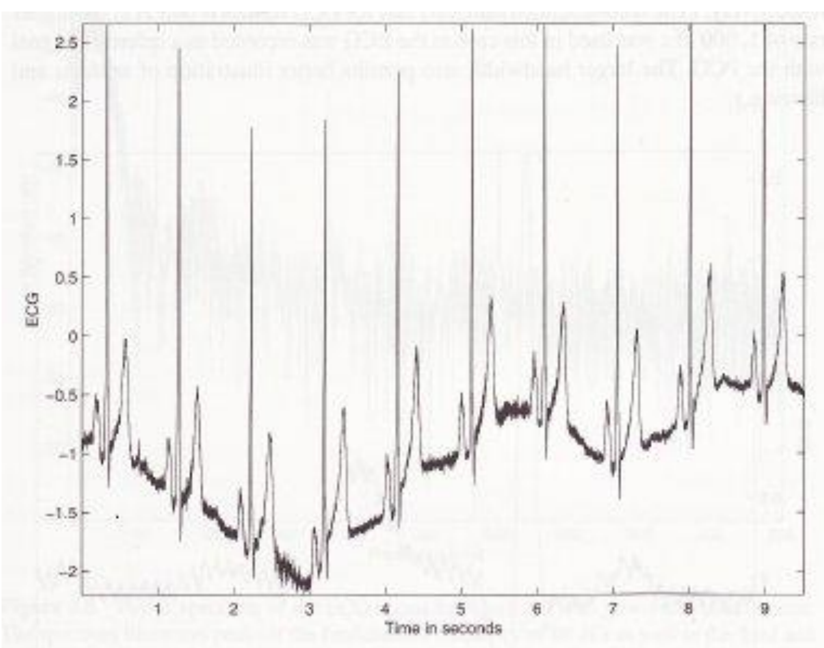


Figure 3.6 ECG signal with low-frequency artifact.

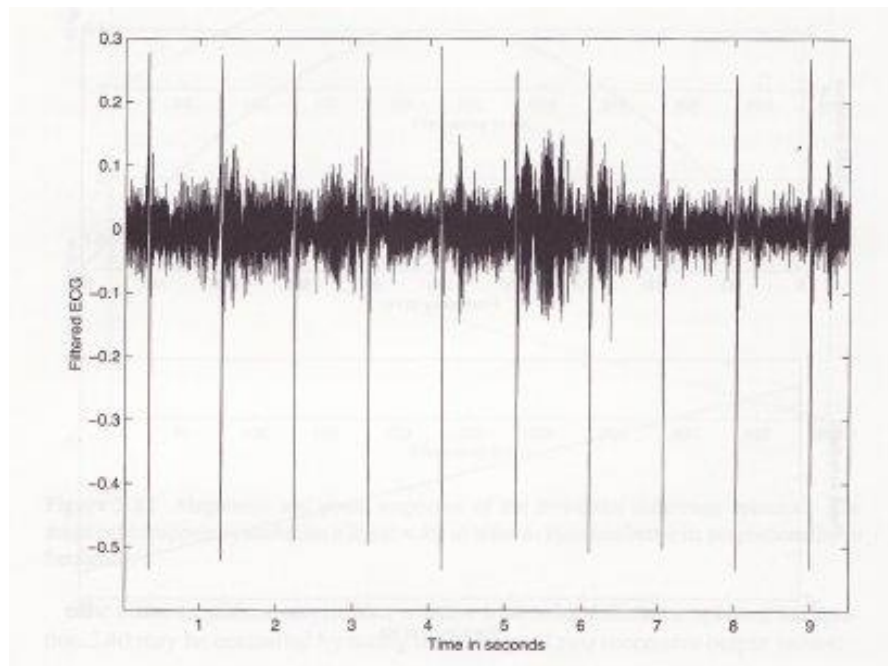


Figure 3.24 Result of filtering the ECG signal with low-frequency noise shown in Figure 3.6, using the first-order difference operator.

Difference filtering, version 2

Modified first-order difference operator:
- T=sampling interval
- Additional pole inserted at zero frequency to steepen the transition band

$$H(z) = \frac{1}{T}\left[\frac{1-z^{-1}}{1-0.995z^{-1}}\right]$$

$$y(n) = \frac{1}{T}[x(n)-x(n-1)] + 0.995y(n-1)$$

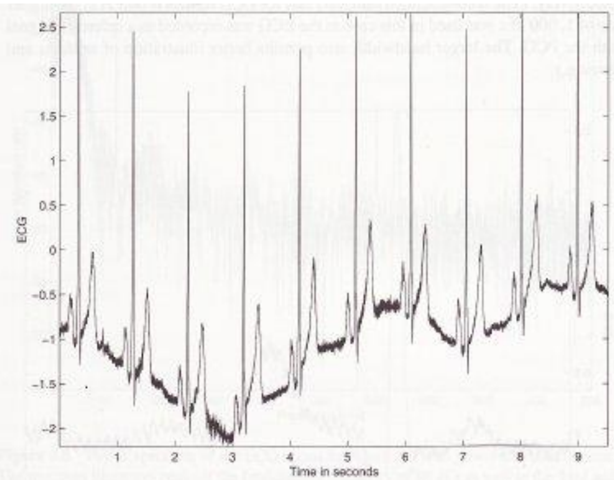


Figure 3.6 ECG signal with low-frequency artifact.

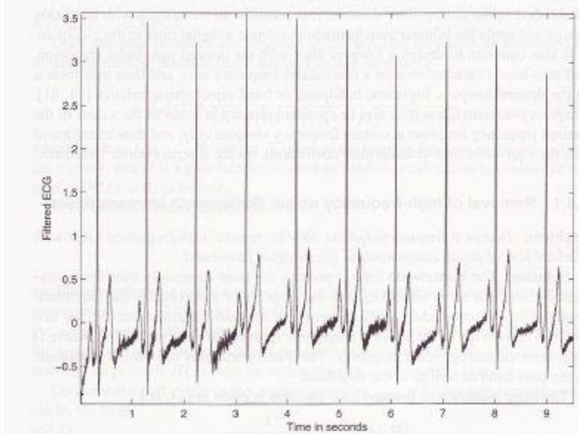


Figure 3.28 Result of processing the ECG signal with low-frequency noise shown in Figure 3.6, using the filter to remove base-line wander as in Equation 3.47. (Compare with the results in Figures 3.24 and 3.25.)

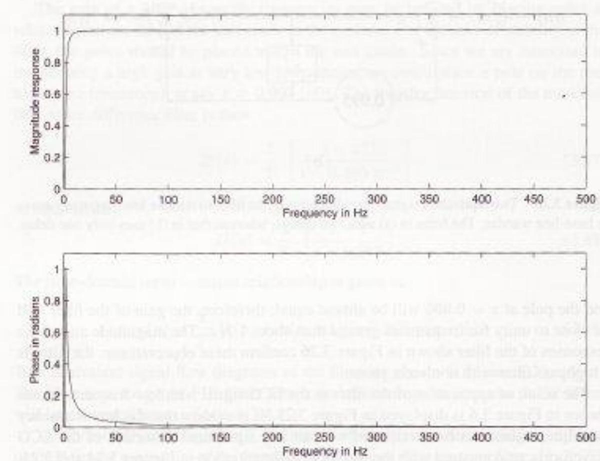


Figure 3.27 Normalized magnitude and phase responses of the filter to remove base-line wander as in Equation 3.47. The magnitude response is shown on a linear scale.

Detrending: Butterworth highpass filter

Select suitable filter order and cutoff frequency

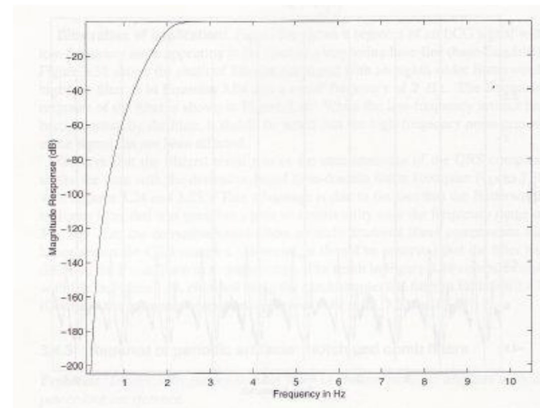


Figure 3.39 Frequency response of an eighth-order Butterworth highpass filter with cutoff frequency = 2 Hz. $f_s = 1,000\ Hz$. The frequency response is shown on an expanded scale for the range $0 - 10\ Hz$ only.

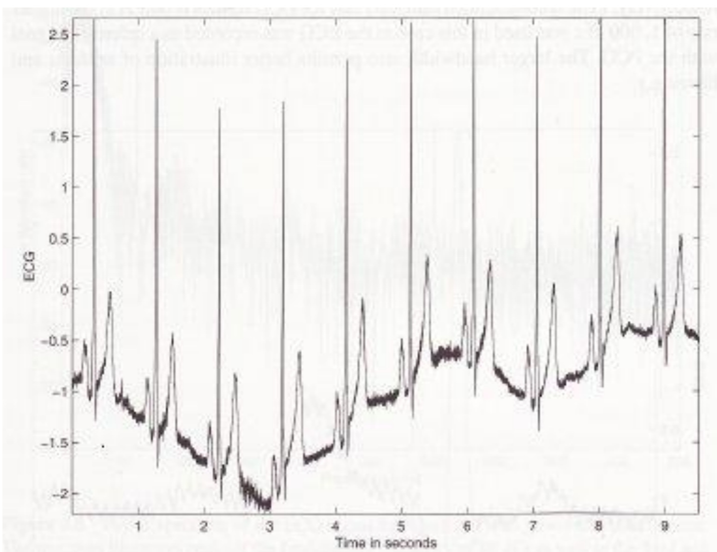


Figure 3.6 ECG signal with low-frequency artifact.

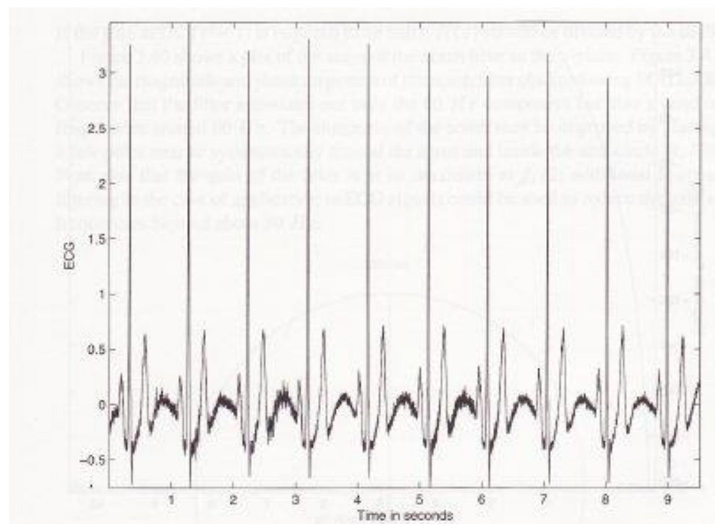


Figure 3.38 Result of frequency-domain filtering of the ECG signal with low-frequency noise in Figure 3.6 with an eighth-order Butterworth highpass filter with cutoff frequency = 2 Hz. (Compare with the results in Figures 3.24, 3.25, and 3.28.)

Savitzky-Golay filter

- S-G filters are called polynomial or least-squares smoothing filters
- Fits a polynomial of given degree optimally to a signal window
- In a sliding time window (frame), a polynomial curve is fitted to signal, and its middle value in the frame is taken as the smoothened value within the window
- Detrending procedure: subtract the smoothed/filtered signal from the original signal
  - This allows for decomposition of the signal into a trend signal and residual/detail signal
  - The trend component can be interpreted as the useful signal component or the noise component, depending on the application
- Can be implemented as a fast FIR filter

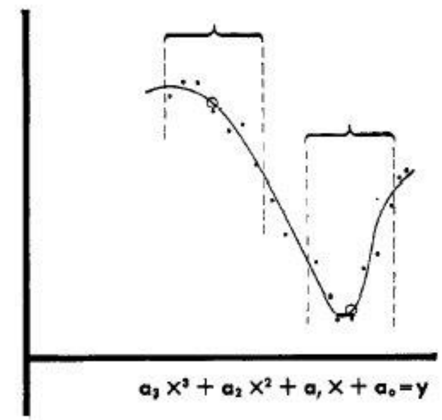
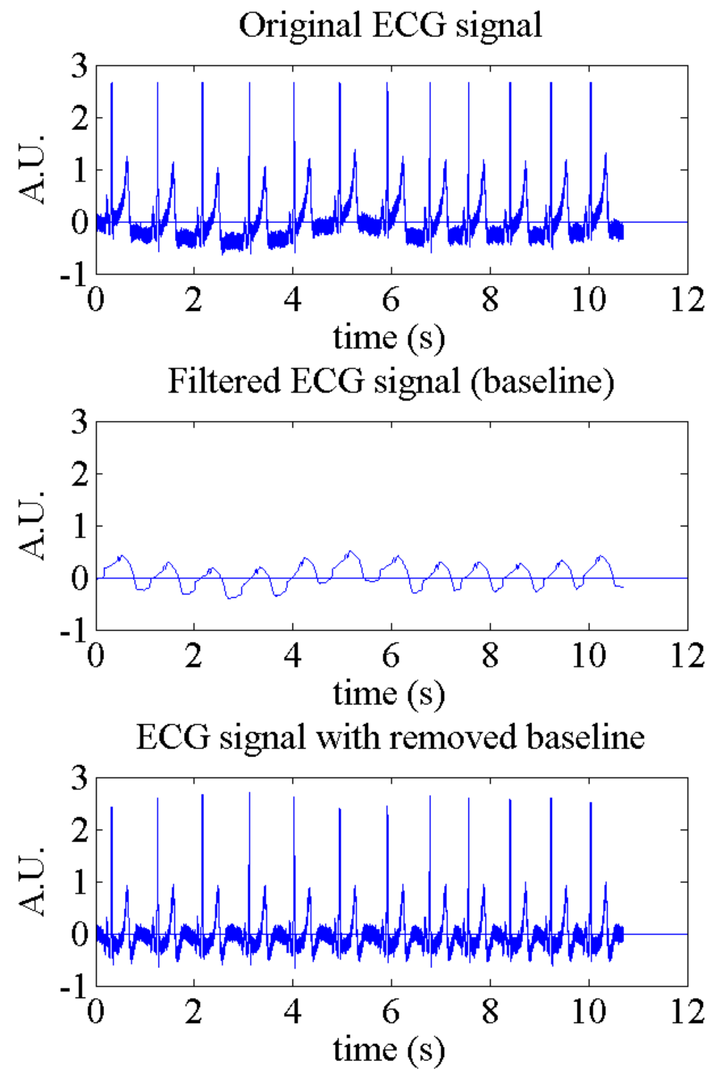


Figure 4. Representation of a 7-point moving polynomial smooth

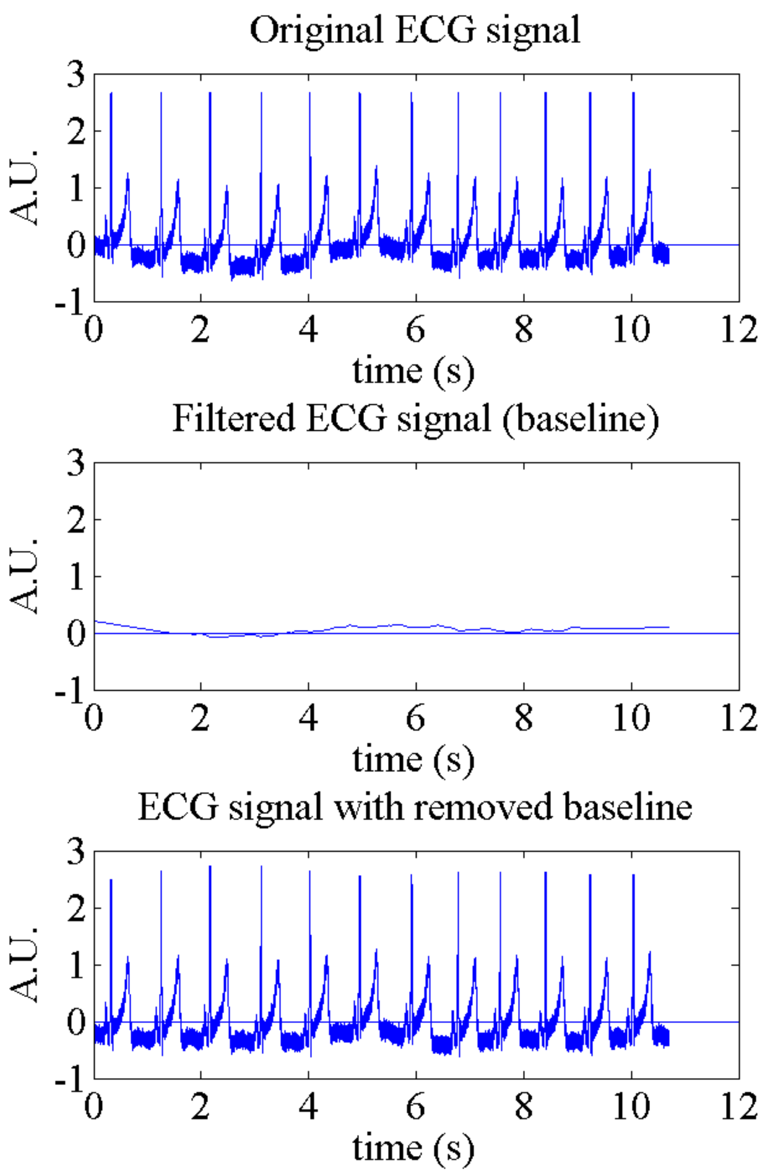
Savitzky-Golay: detrending example with ECG

- Parameters:
  - Degree of polynomial (usually 1 or 2)
  - Window/frame size
    - depends on signal's timing properties and, thus, sampling frequency
- Parameter selection affects strongly the filtering results:
  - The higher degree the polynomial is, the more the small details are followed and removed in the output signal!
  - Figure on right: too high polynomial was used: the baseline estimate follows ECG shapes too closely and removes important information!



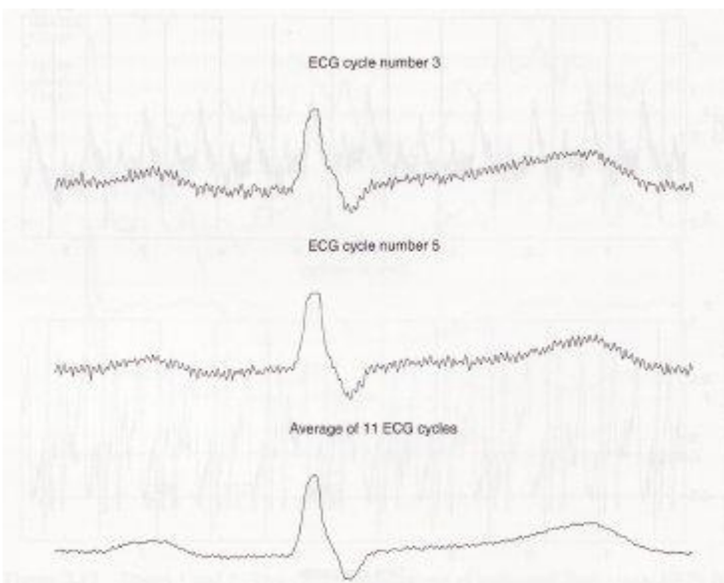
Savitzky-Golay: detrending example with ECG, cont'd

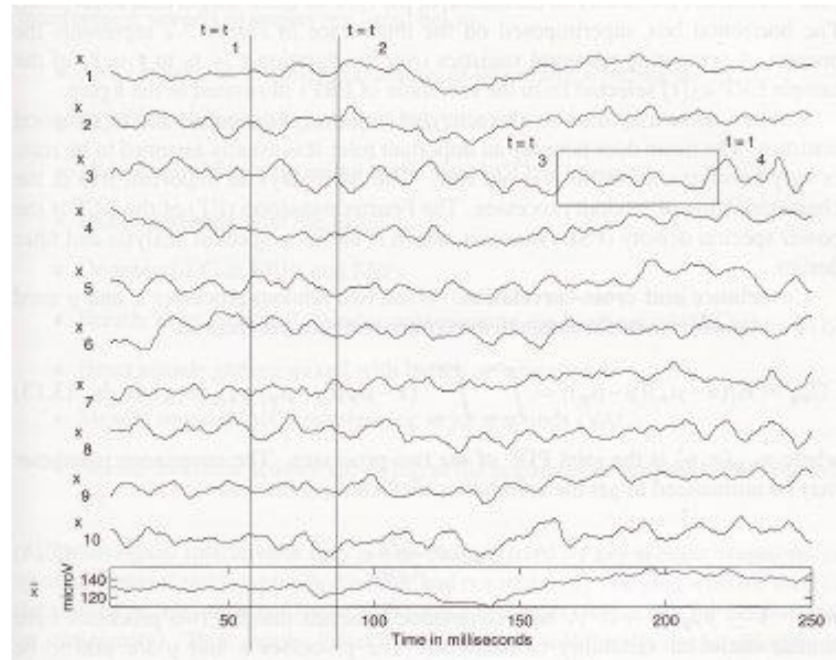
- Figure on right: more proper polynomial degree (low) was used: the baseline estimate follows the trend better
  - The ECG waveforms are retained better (in the bottom figure)



Synchronized averaging

- Filter noise by averaging several signals containing the same events
  - Often simple/complex pulses
- Signals must first be time-synchronized





Averaging of flash visual ERP's from EEG

Central limit theorem: the sum of i.i.d. random variables with finite distributions approaches normal distribution.
With zero mean variables, the sum approaches zero.
Here, the random variables represent noise.

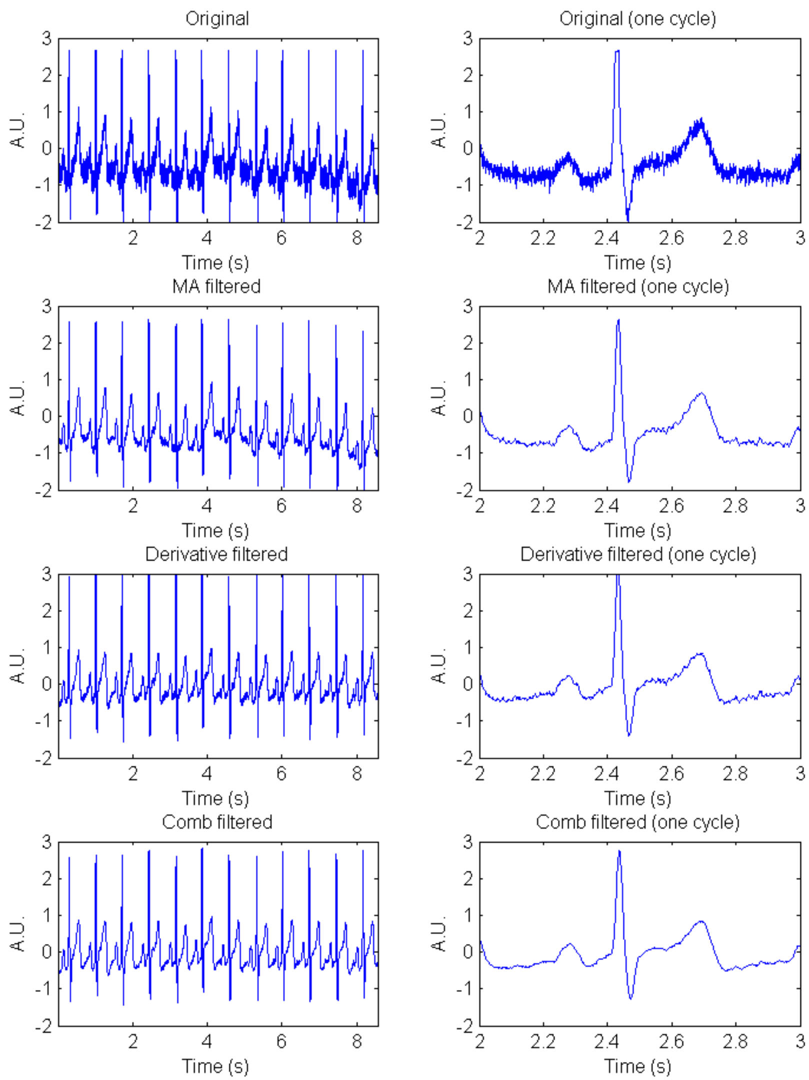
Example case of multi-stage filtering

Filtering many noise types

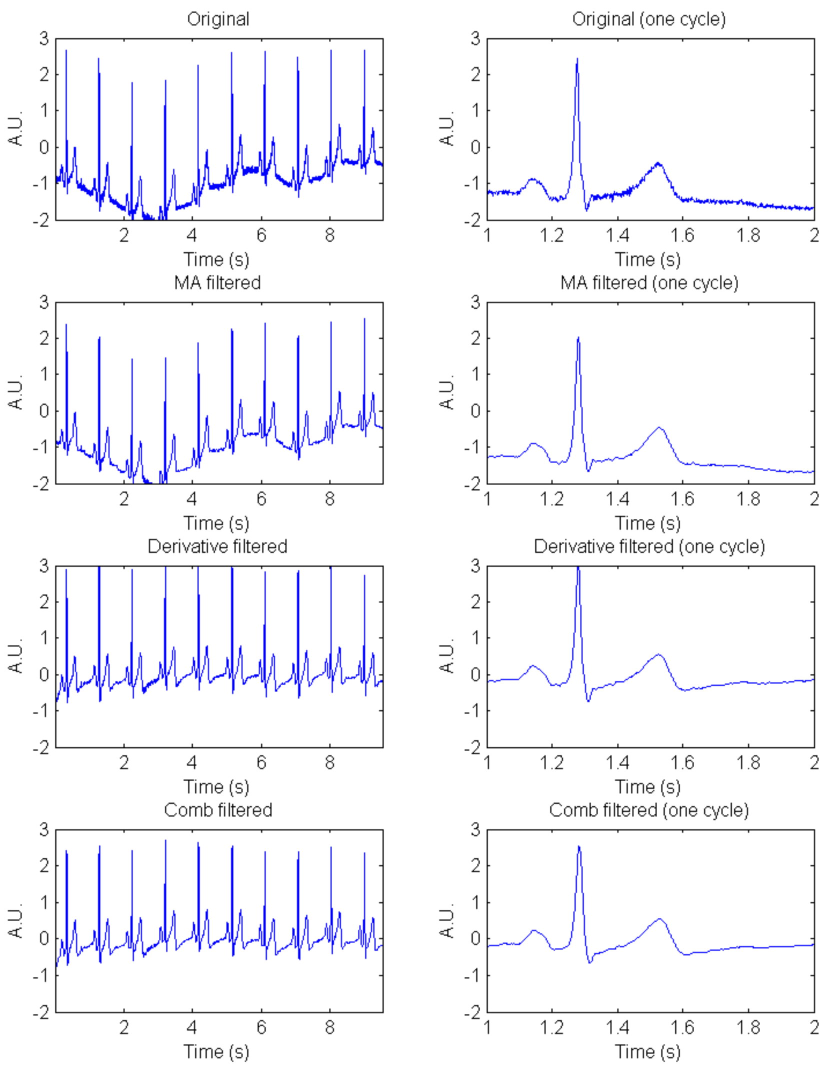
- Often the signal contains different kinds of noise
- A pipeline must be designed so that each stage removes one type of noise
- Filter stages can sometimes be combined into one stage
  - E.g.: LP + HP -> BP

- An example filter pipeline:

Filtering many noise types: example result 1



Filtering many noise types: example result 2



Selected references

Course book: Chapter 3

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