Spectral Analysis and Heart Rate Variability: Principles and Biomedical Applications

Dr. Harvey N. Mayrovitz

Why Spectral Analysis?

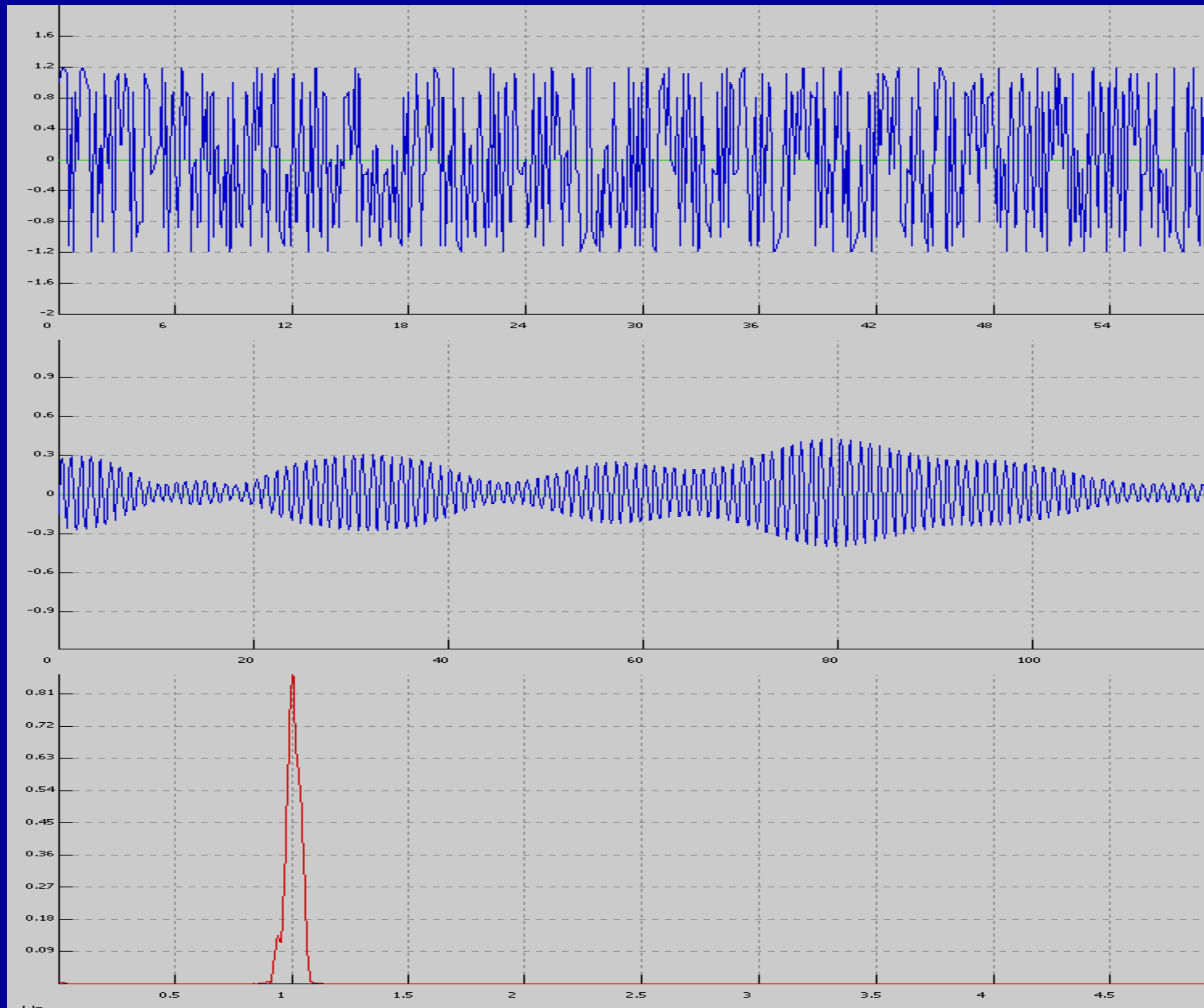
Detection and characterization of cyclical or periodic processes present in physiological signals

Rhythms are present in nearly all physiological signals - but not always evident to the 'naked eye'!

Signal

Filtered

Spectrum

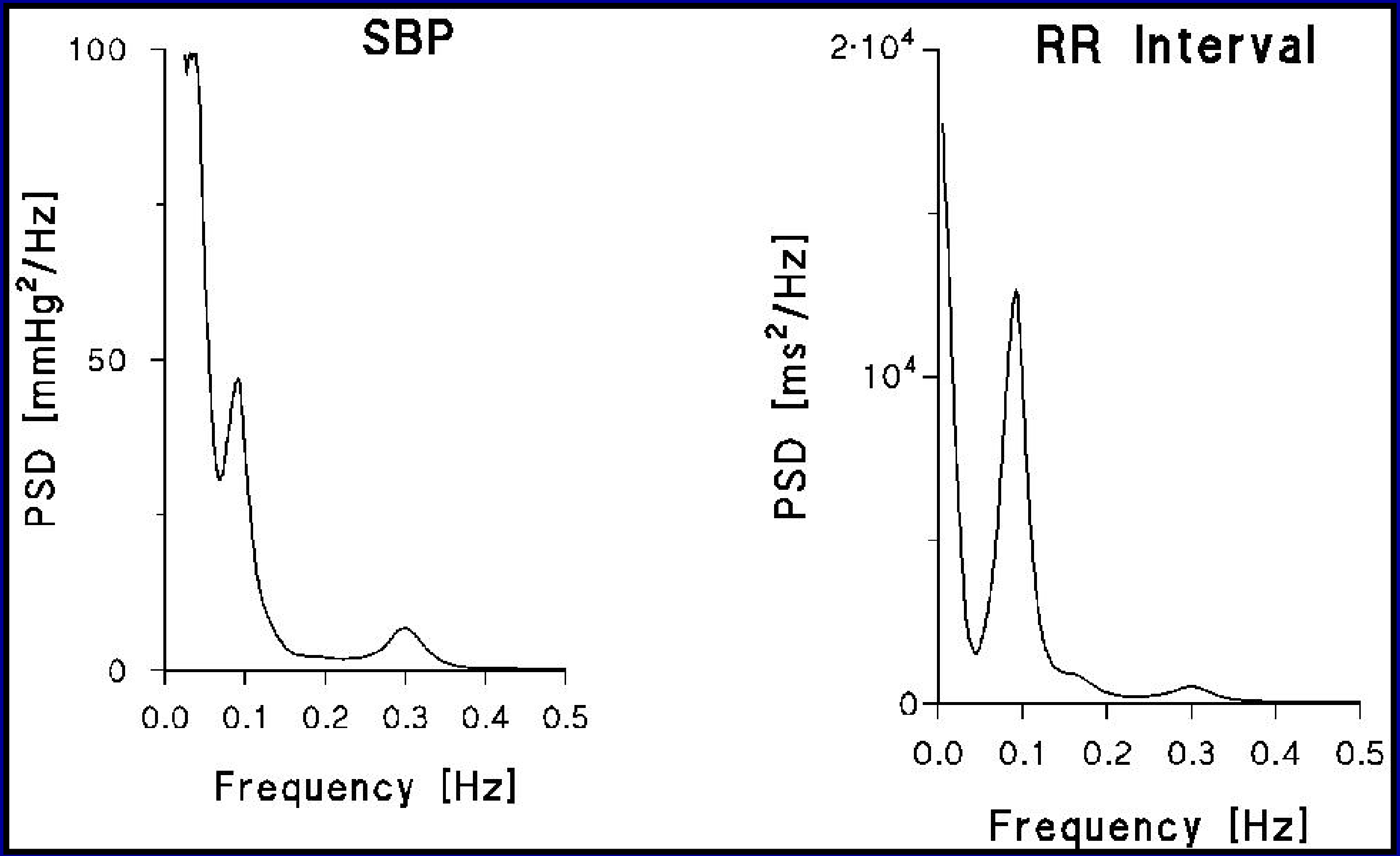


How do you
extract spectral (frequency)
components present in
physiological signals?

Power Spectral Density

Amount of power per unit (density) of frequency (spectral) as a function of frequency

PSD describes how the power (or variance) of a time series is distributed with frequency!



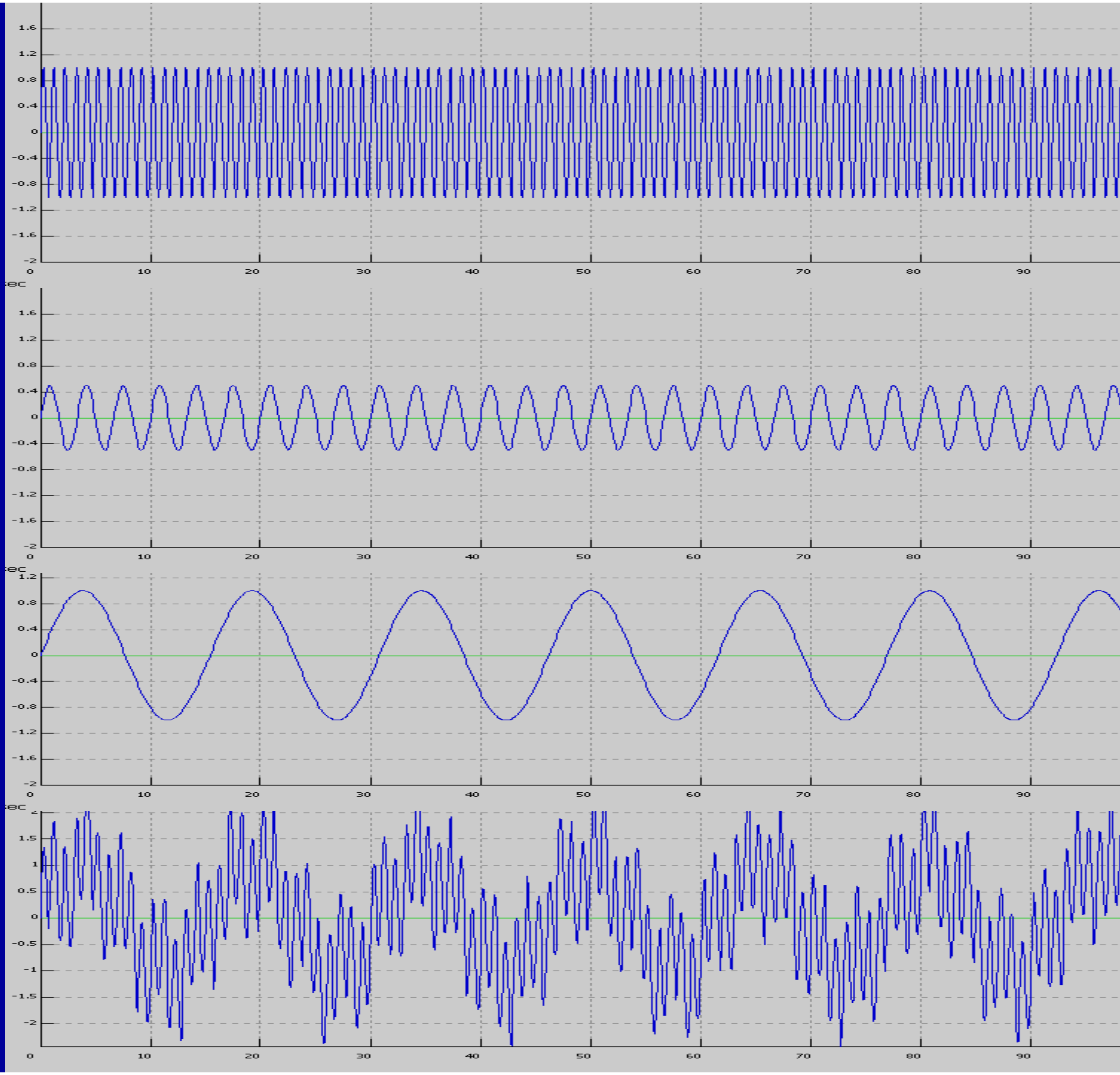
Example with Simulated Signals

A
1.0 Hz

B
0.3 Hz

C
0.065 Hz

A+ B+ C



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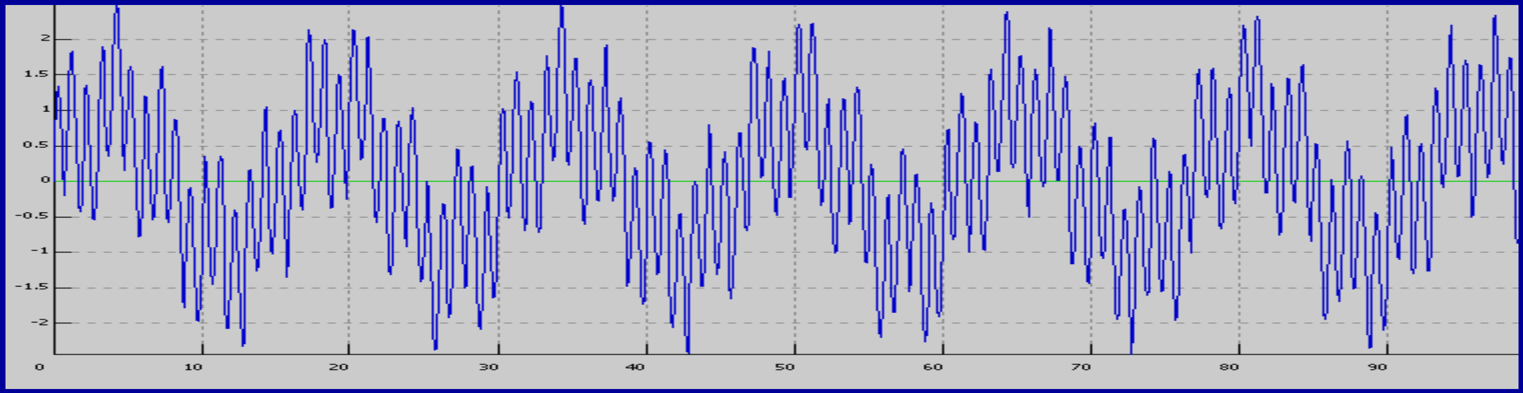
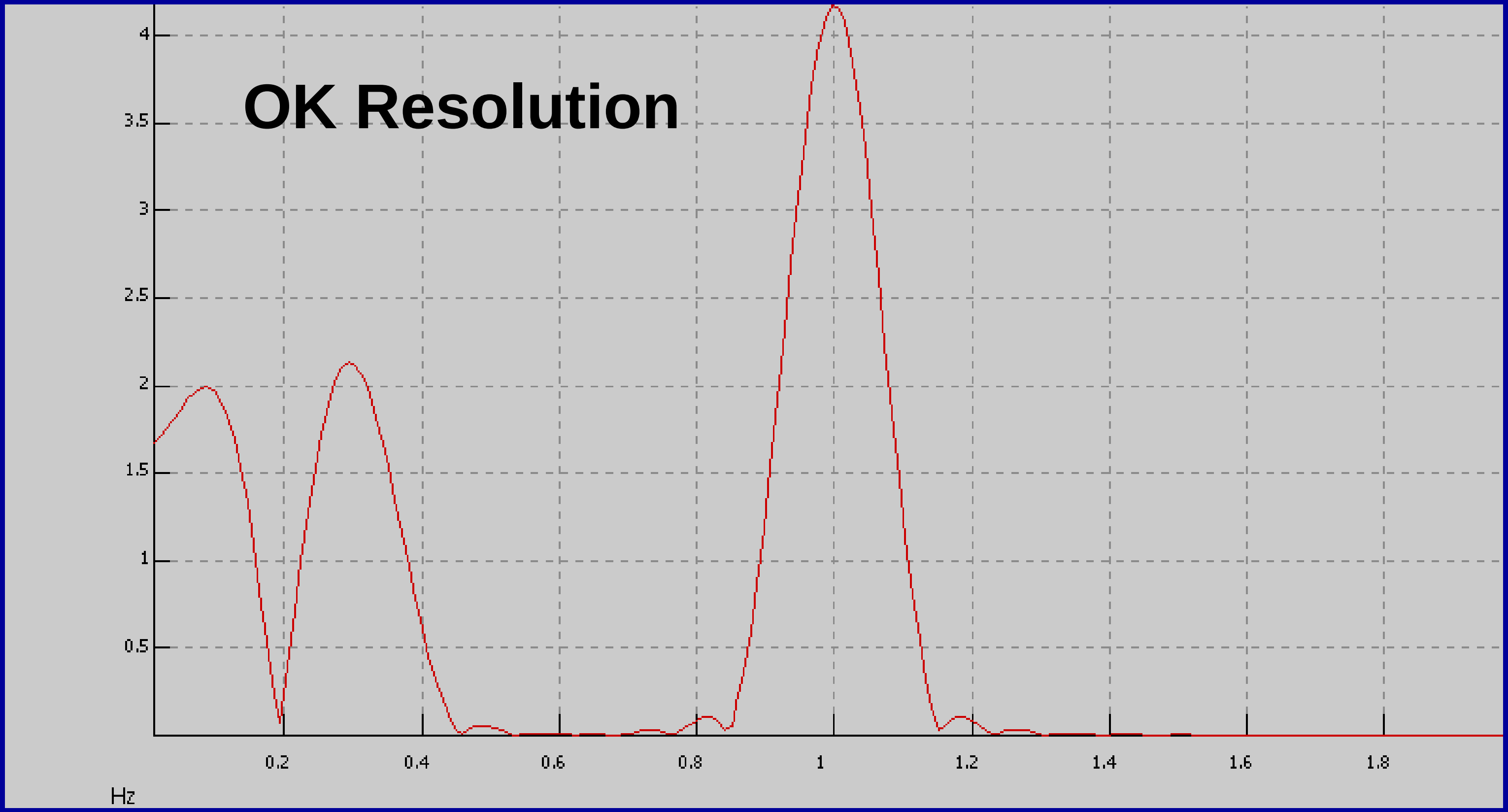
A+ B+ C

100 sec





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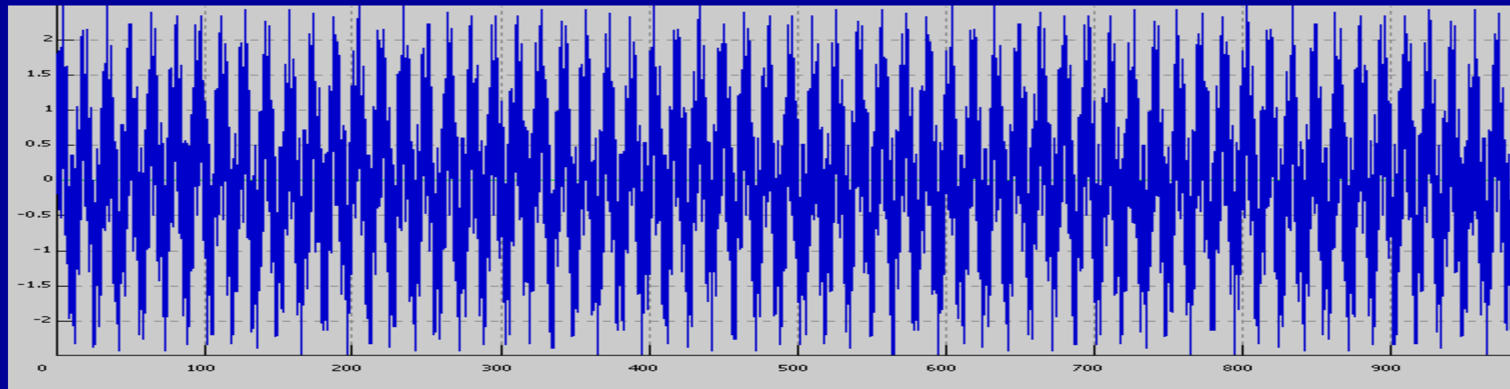
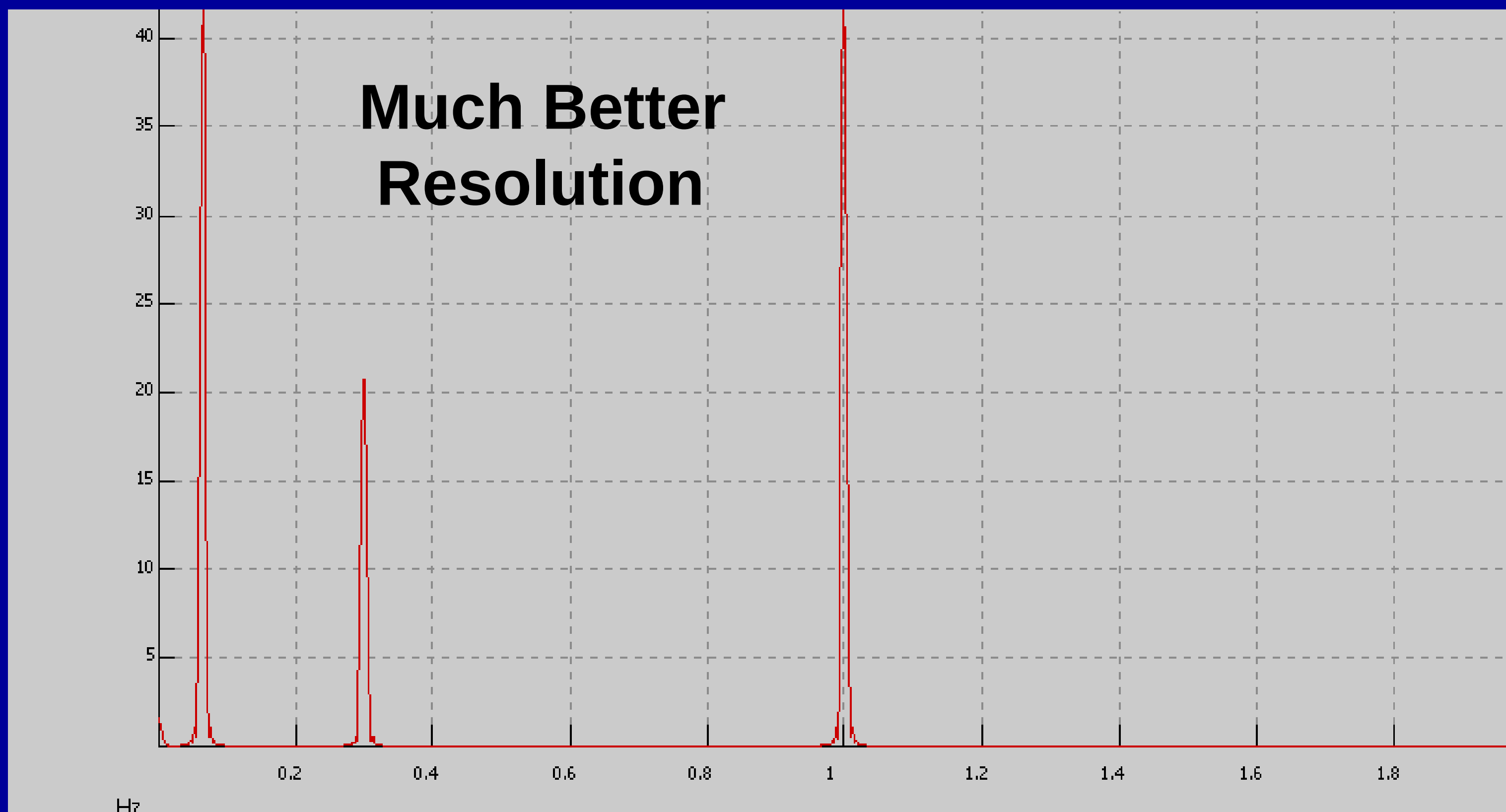
A+ B+ C

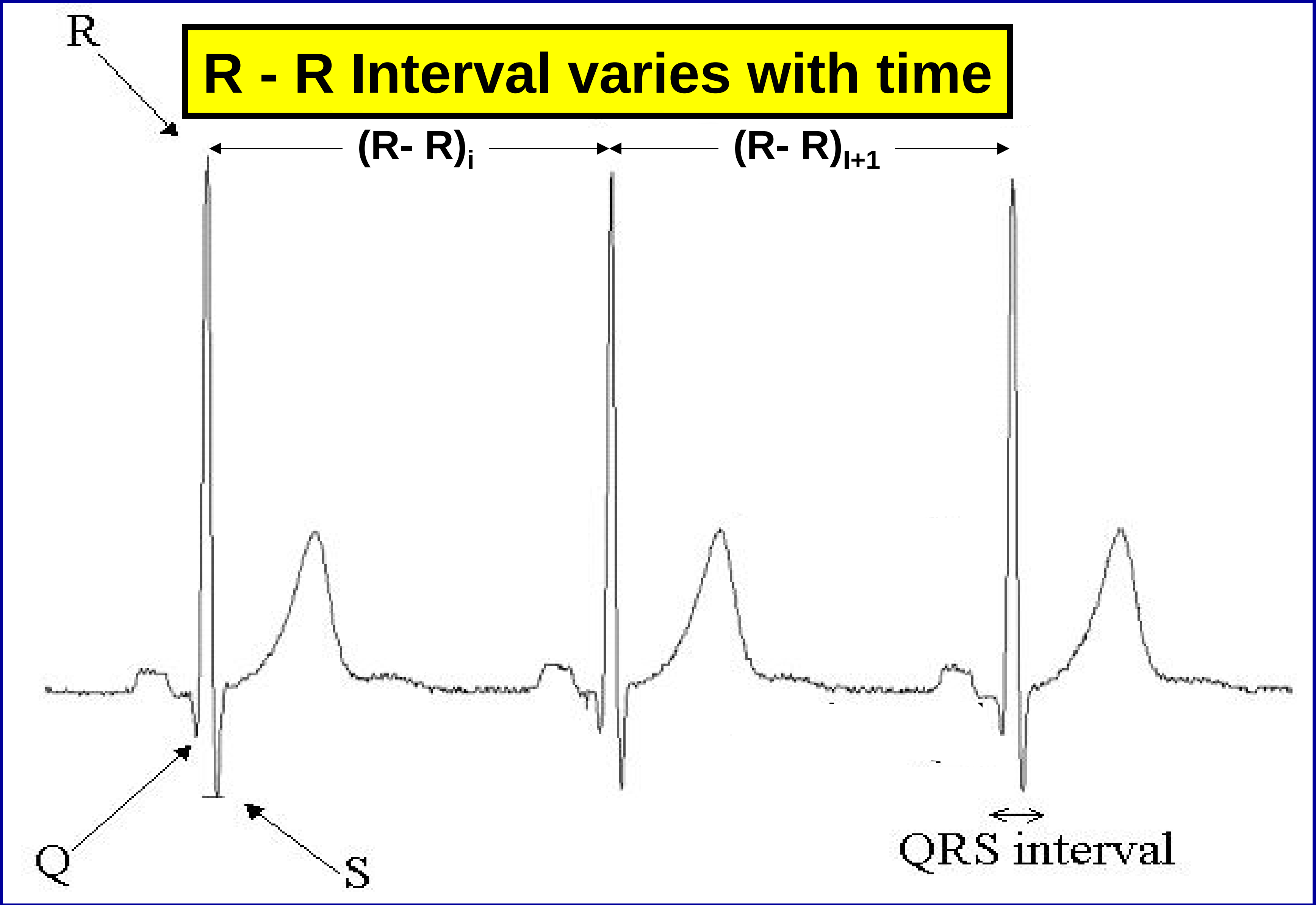
1000 sec


2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
100
200
300
400
500
600
700
800
900

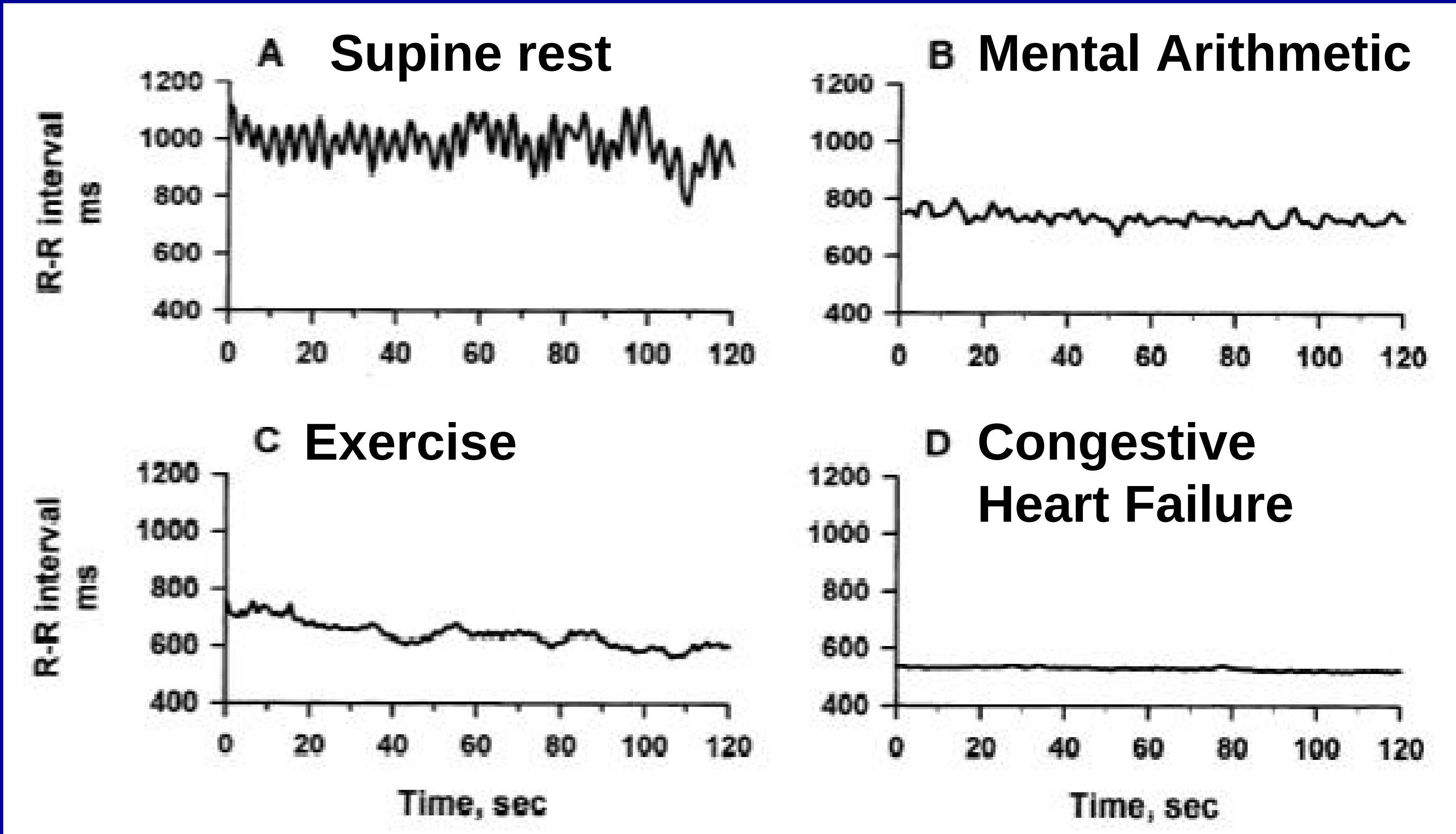

Much Better Resolution
40
35
30
25
20
15
10
5
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Hz

Generating a time series signal from the Electrocardiogram

R- R Time Series

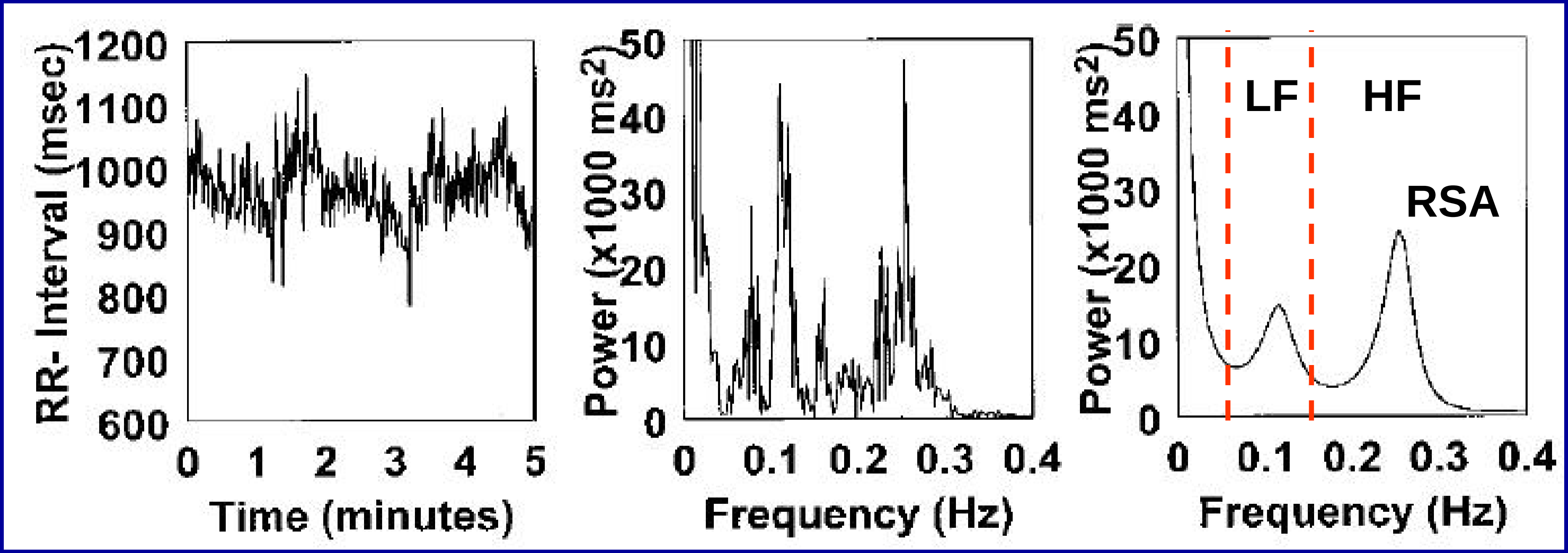


R- R Time Series



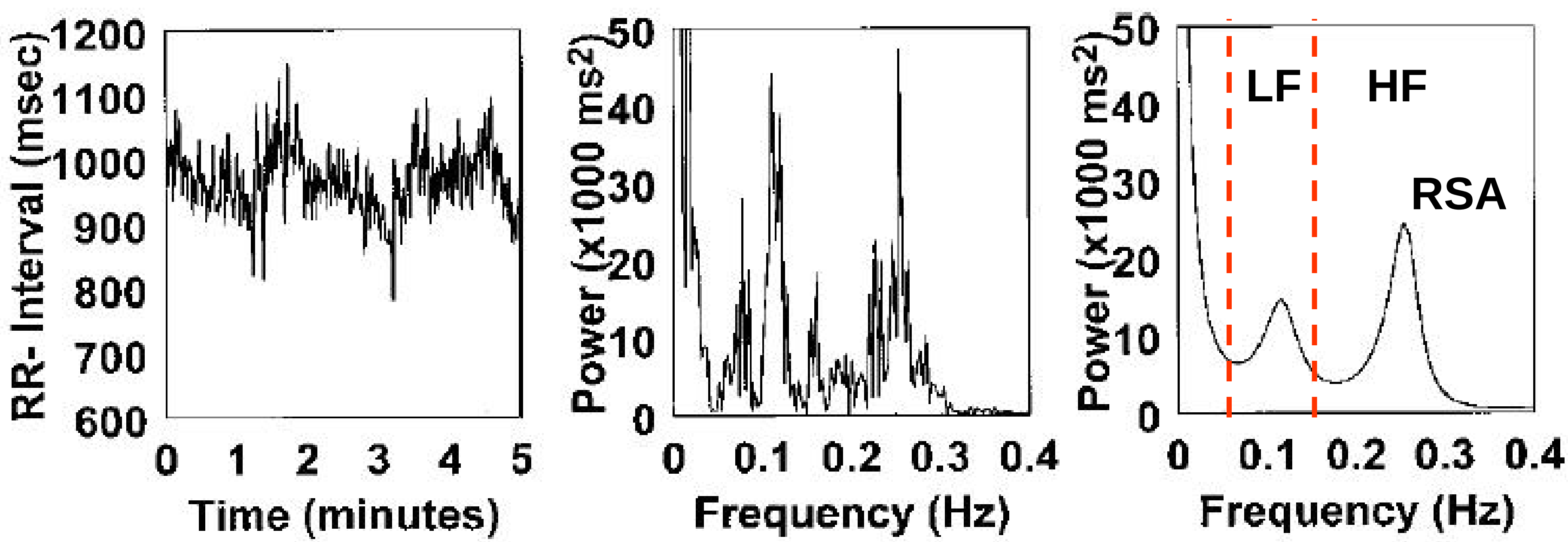
Heart Rate Variability

Heart Rate Variability (HRV)

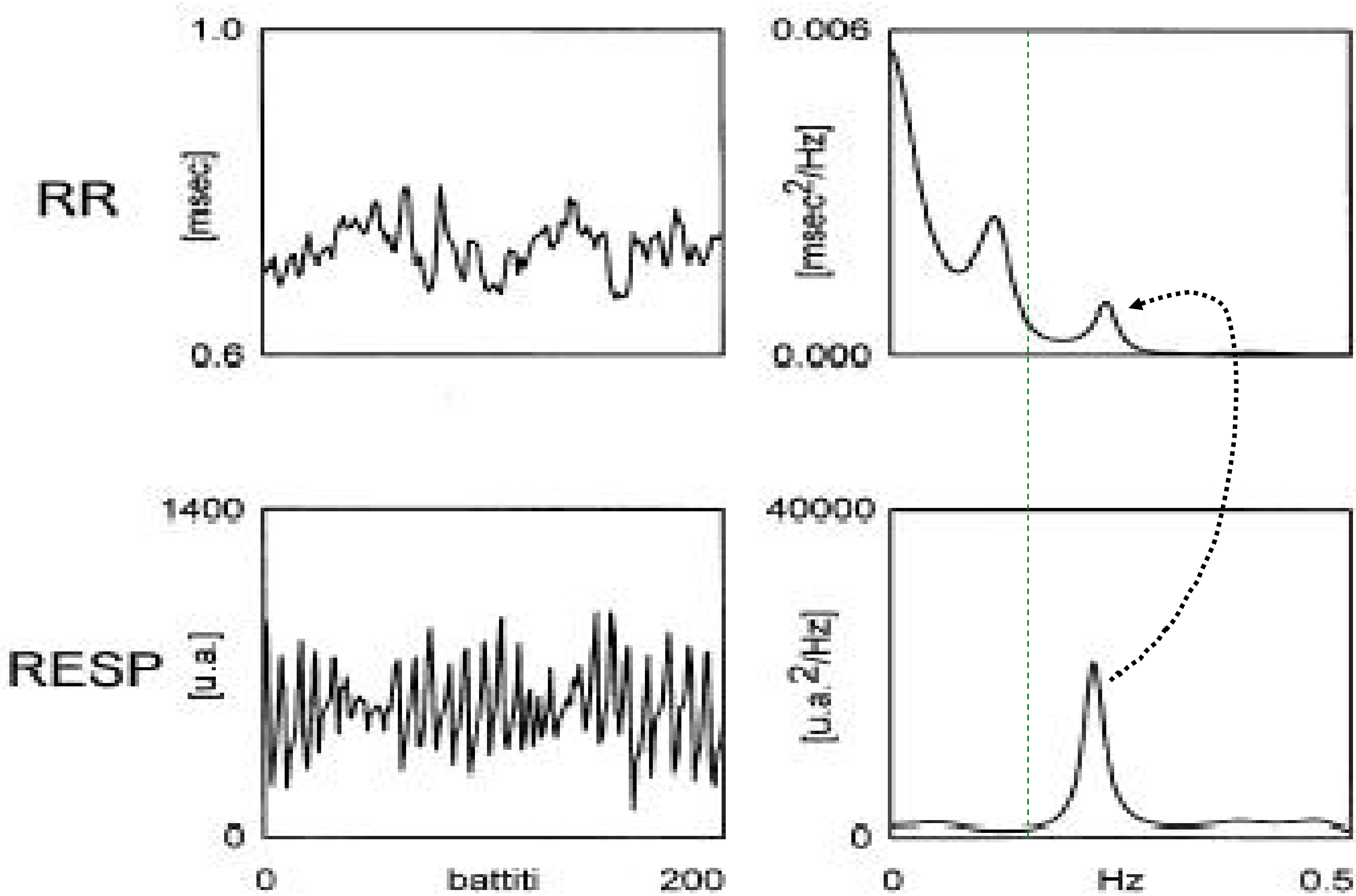


Heart Rate Variability (HRV)

		ULF: <0.003 Hz
Peripheral Vascular & Thermoregulatory	→	VLF: 0.003 - 0.04 Hz
Baroreceptors phase delay Sympathetic & Parasympathetic	→	LF: 0.04 - 0.15 Hz
Respiratory Sinus Arrhythmia (RSA) Cardiac Vagal Activity Change	→	HF: 0.15 - 0.40* Hz

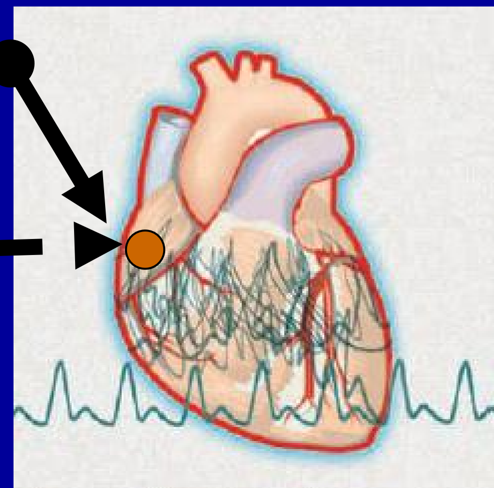


RSA Main Source of HF peak



Respiratory Linkage to HF & LF

Parasympathetic
(Vagus)
Heart Rate Brake



HR changes

Inspiration (inhibits vagus nerve outflow impulses)

- Centrally?
- Increased venous return

↓

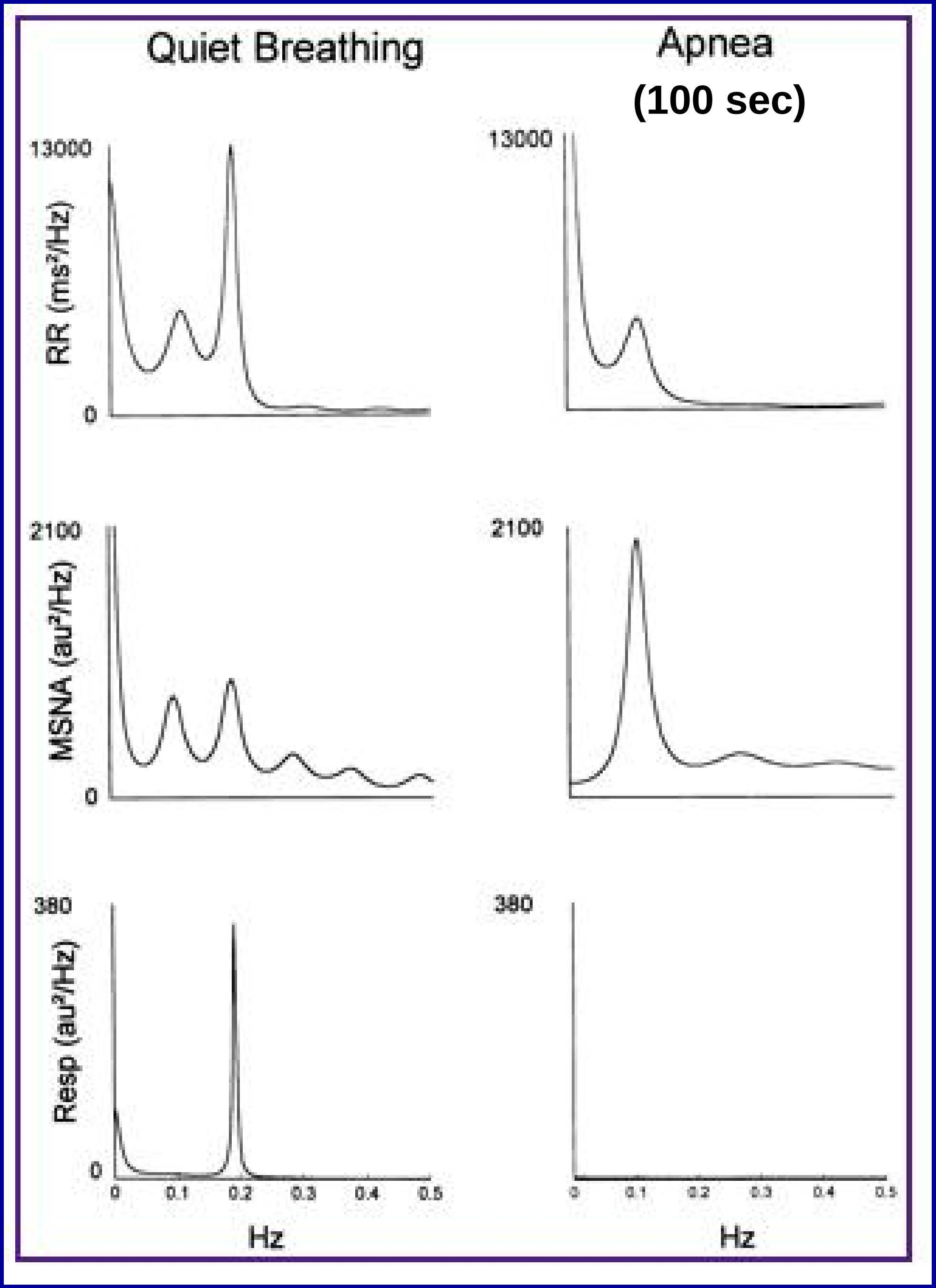
Baroreflex

Vagus ~ Fast ~ HF

Sympathetic

Sympathetic ~ Slow ~ Phase Delay ~ LF

Importance of Respiration

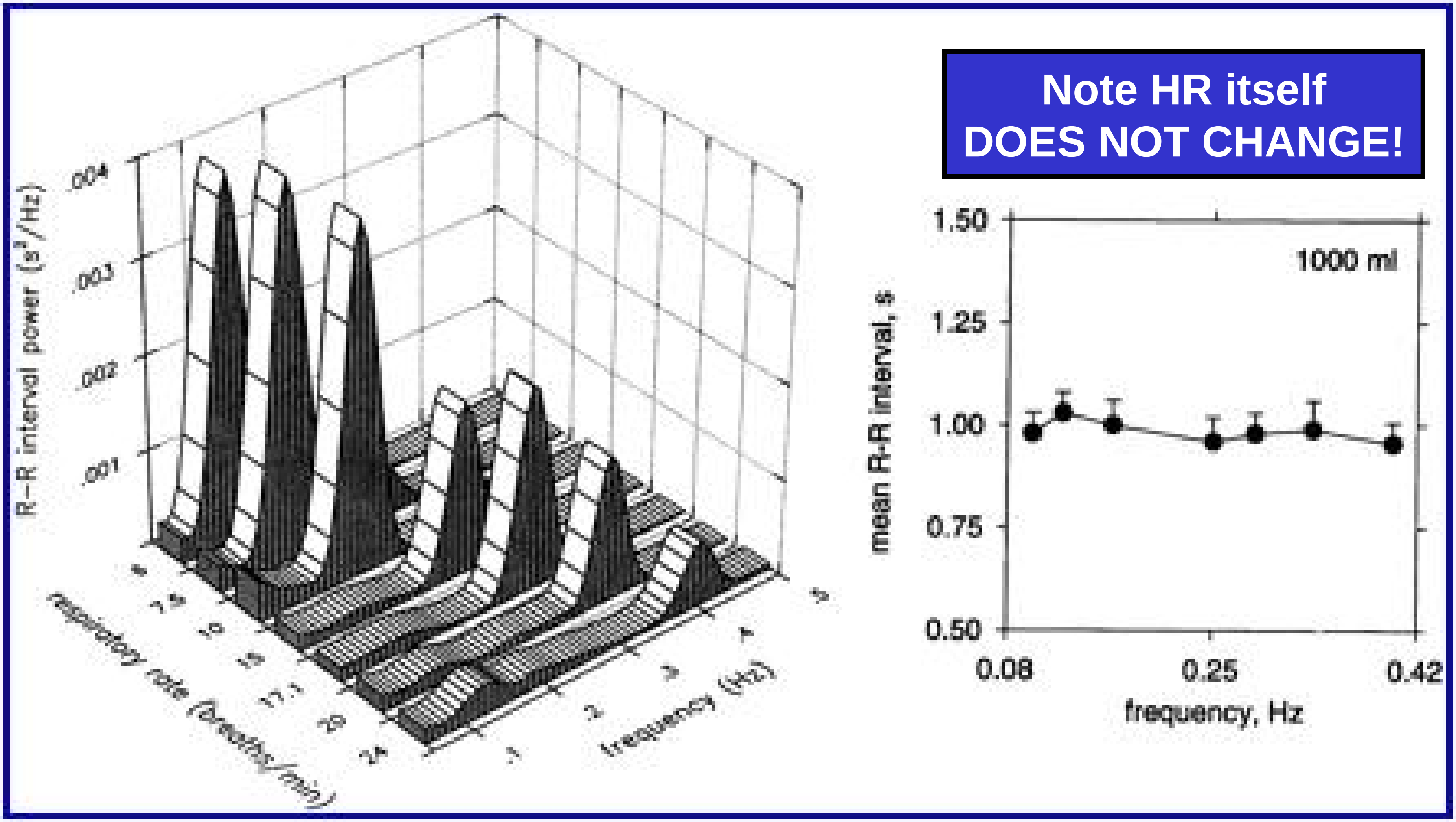


Peroneal nerve sympathetic

Paced Breathing At 0.2 Hz

Slow rate allows fuller expression of Ach effects Resulting in greater HF power at lower frequencies

Note HR itself DOES NOT CHANGE!



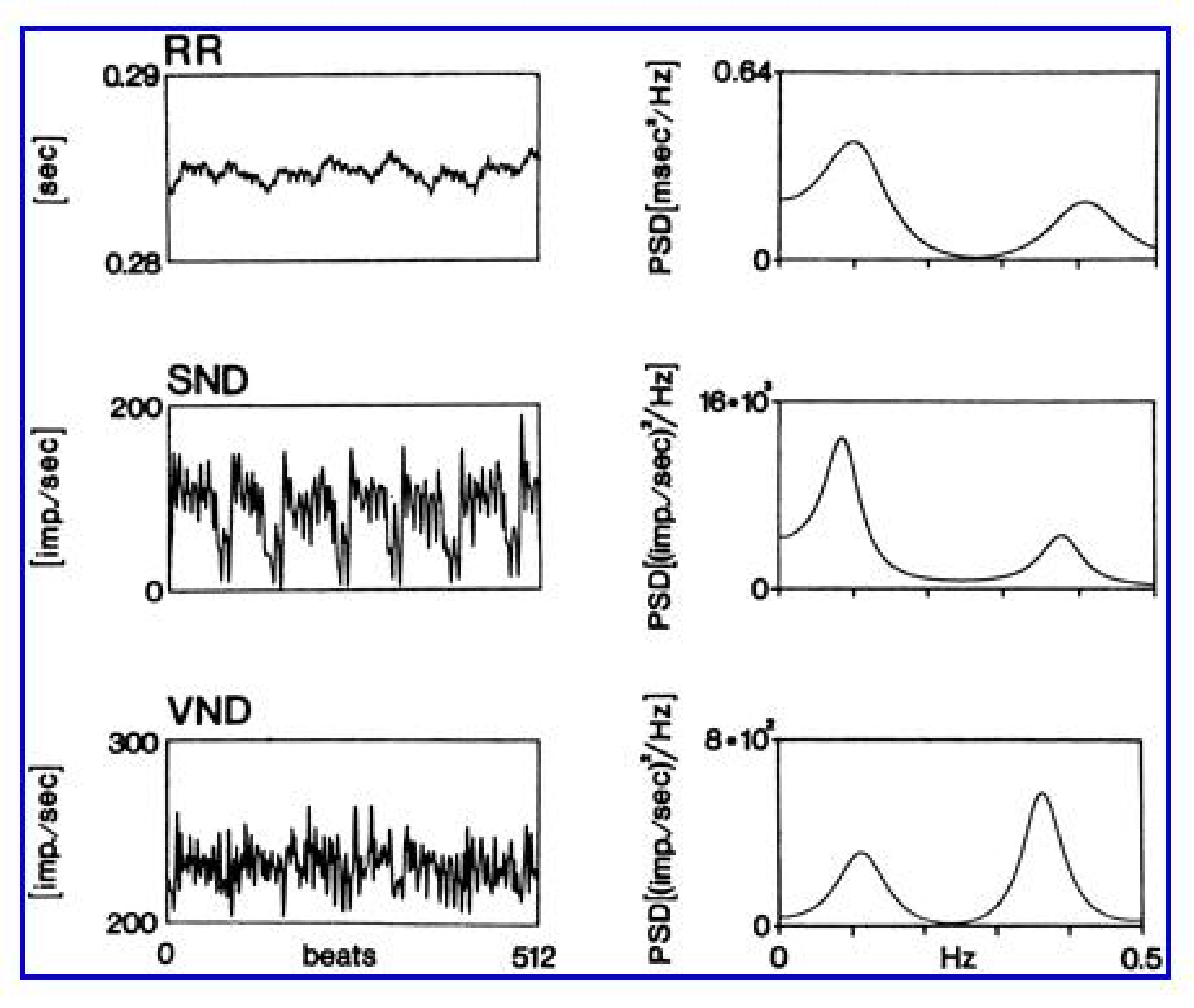
Relationship to Neural Signals

R-R Interval

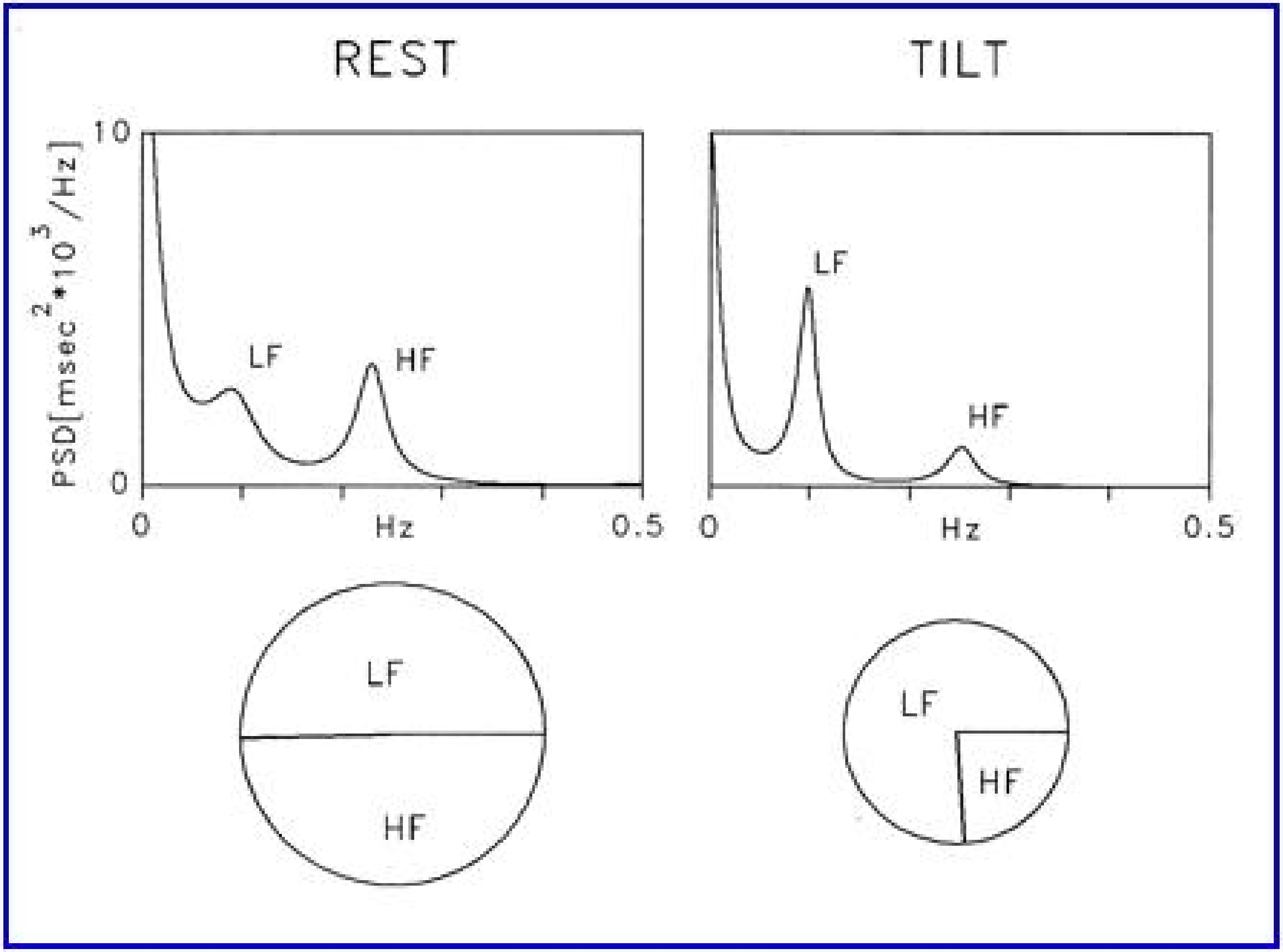
<u>Cardiac Nerve Traffic</u>

Sympathetic

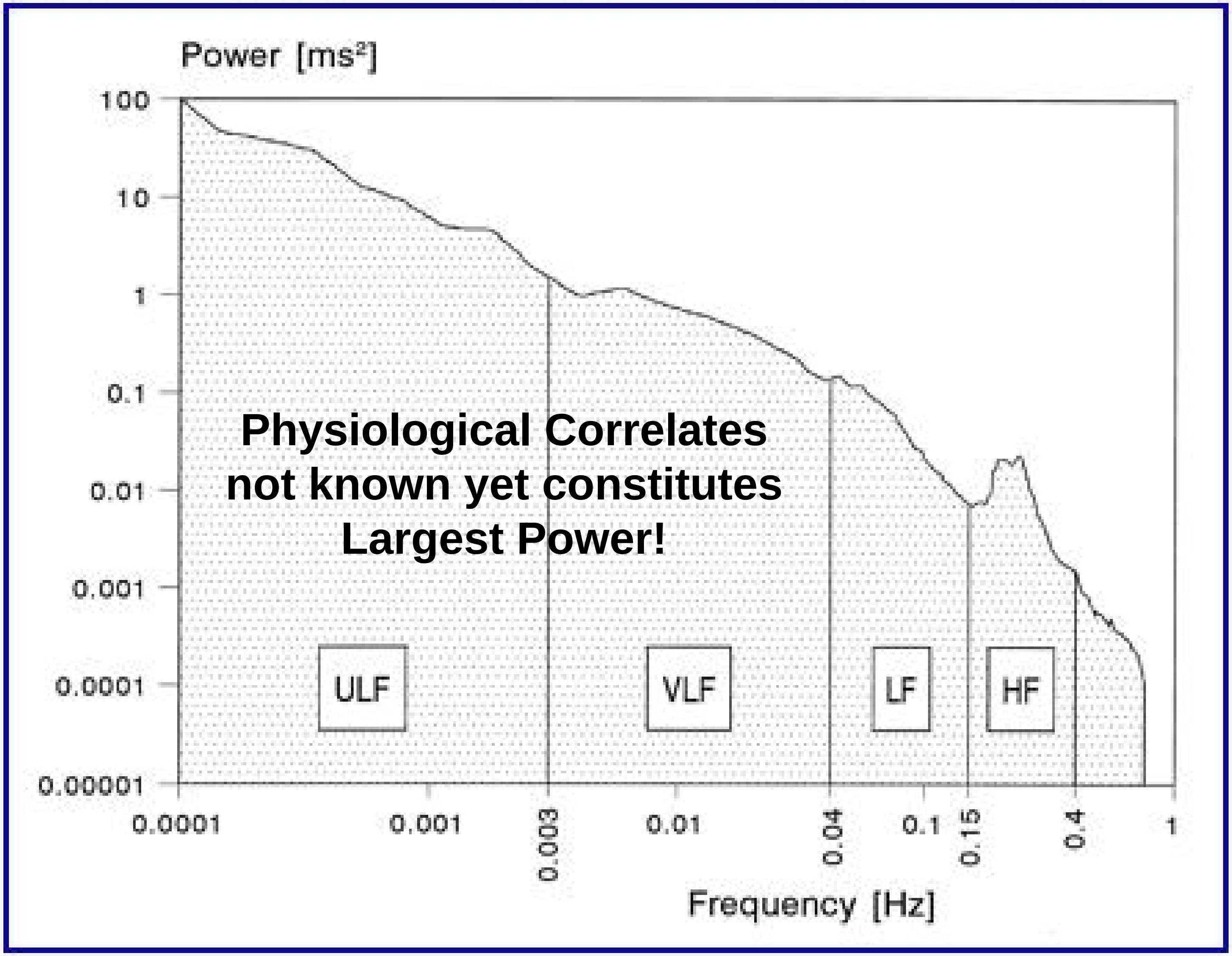
Vagal



Enhancement of Sympathetic Modulation



24 Hour Recording

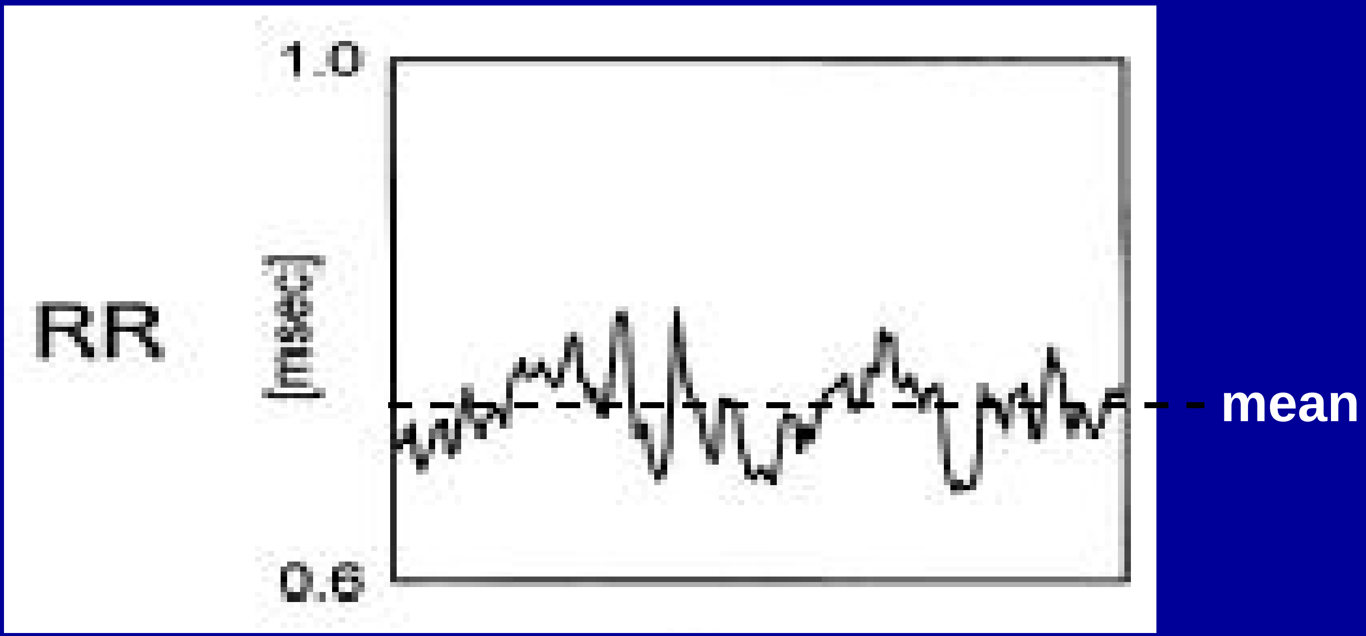


Time Analysis of HRV

uses standard deviation or variance of (normal) R-R intervals

Coefficient of variance = SD/mean

= SDNN/mean



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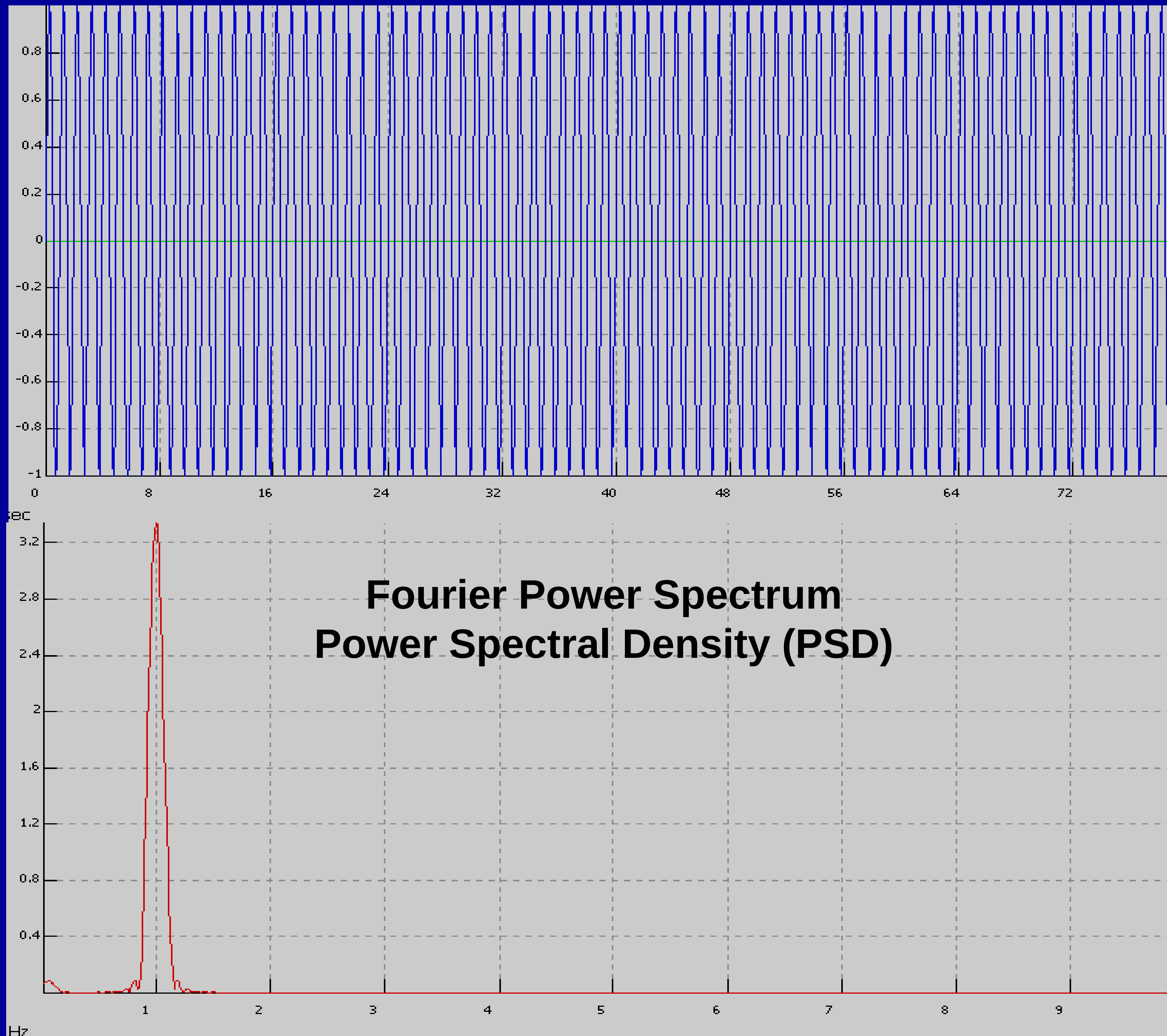
Spectral Analysis Considerations

For a given sampling rate the length of time a signal is sampled sets the Frequency Resolution

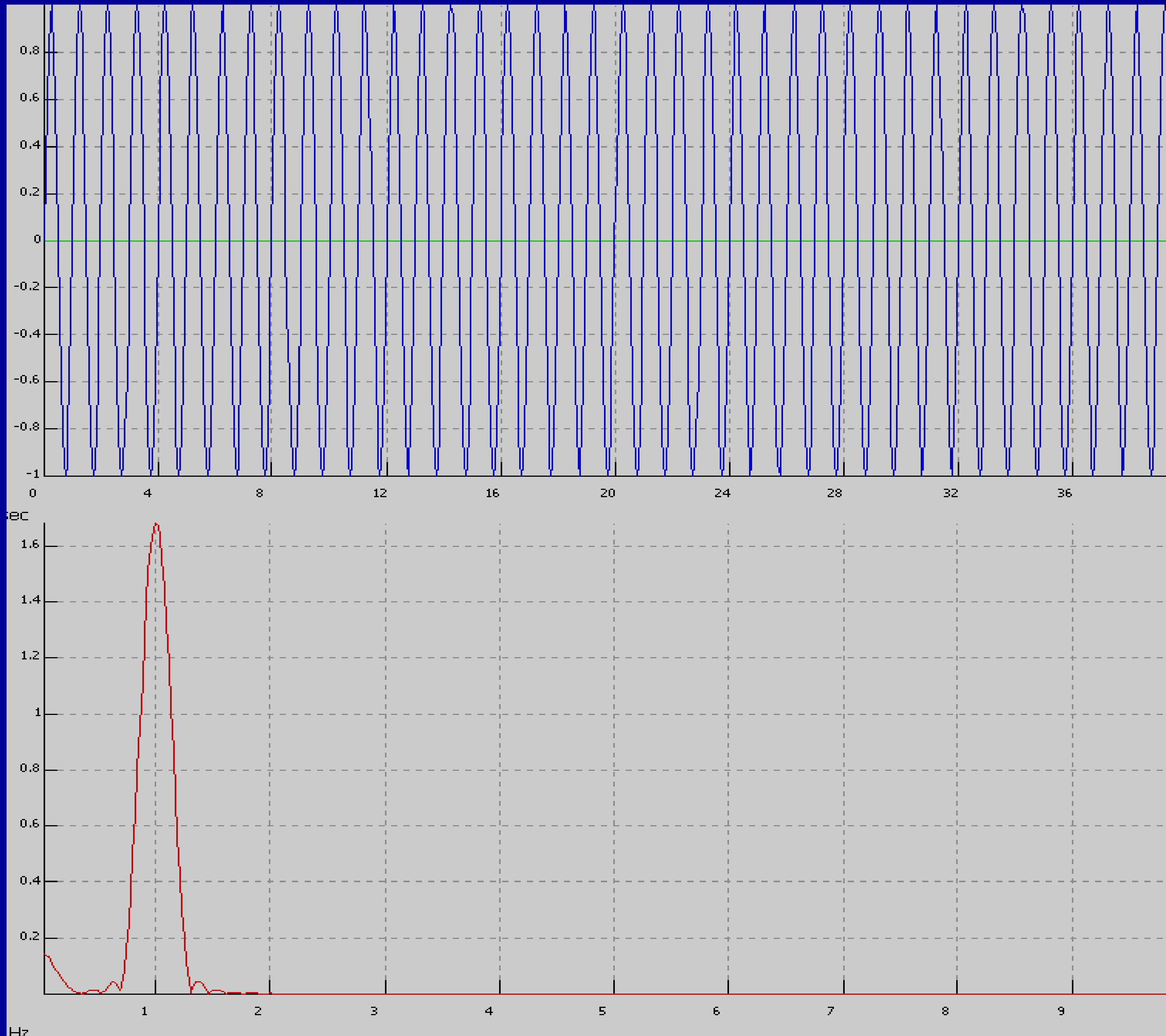
Signal

80 cycles of a 1 Hz sine wave



Signal

40 cycles of a 1 Hz sine wave



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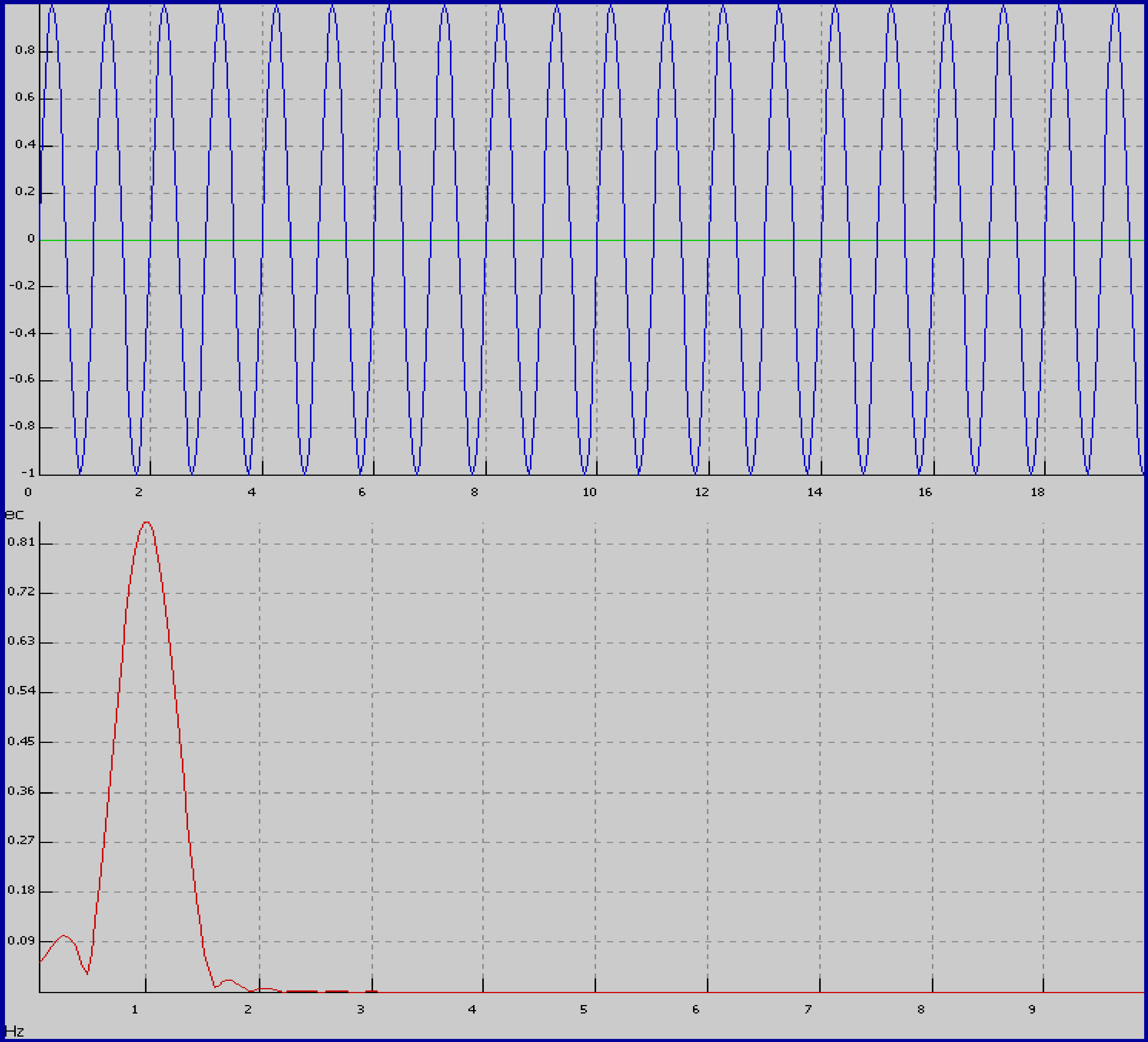
Signal

20 cycles of a 1 Hz sine wave



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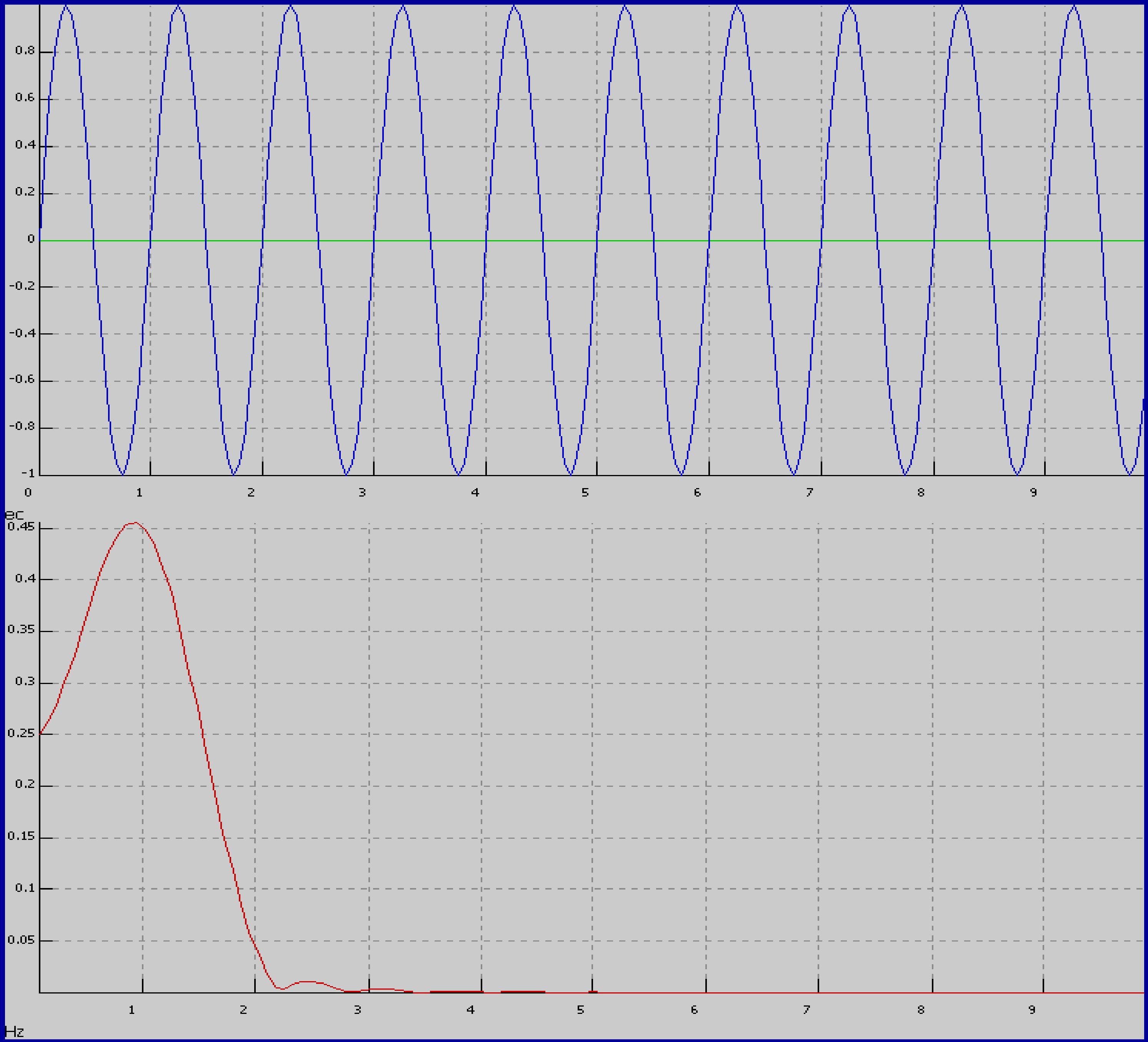
<u>Signal</u>

10 cycles of a 1 Hz sine wave



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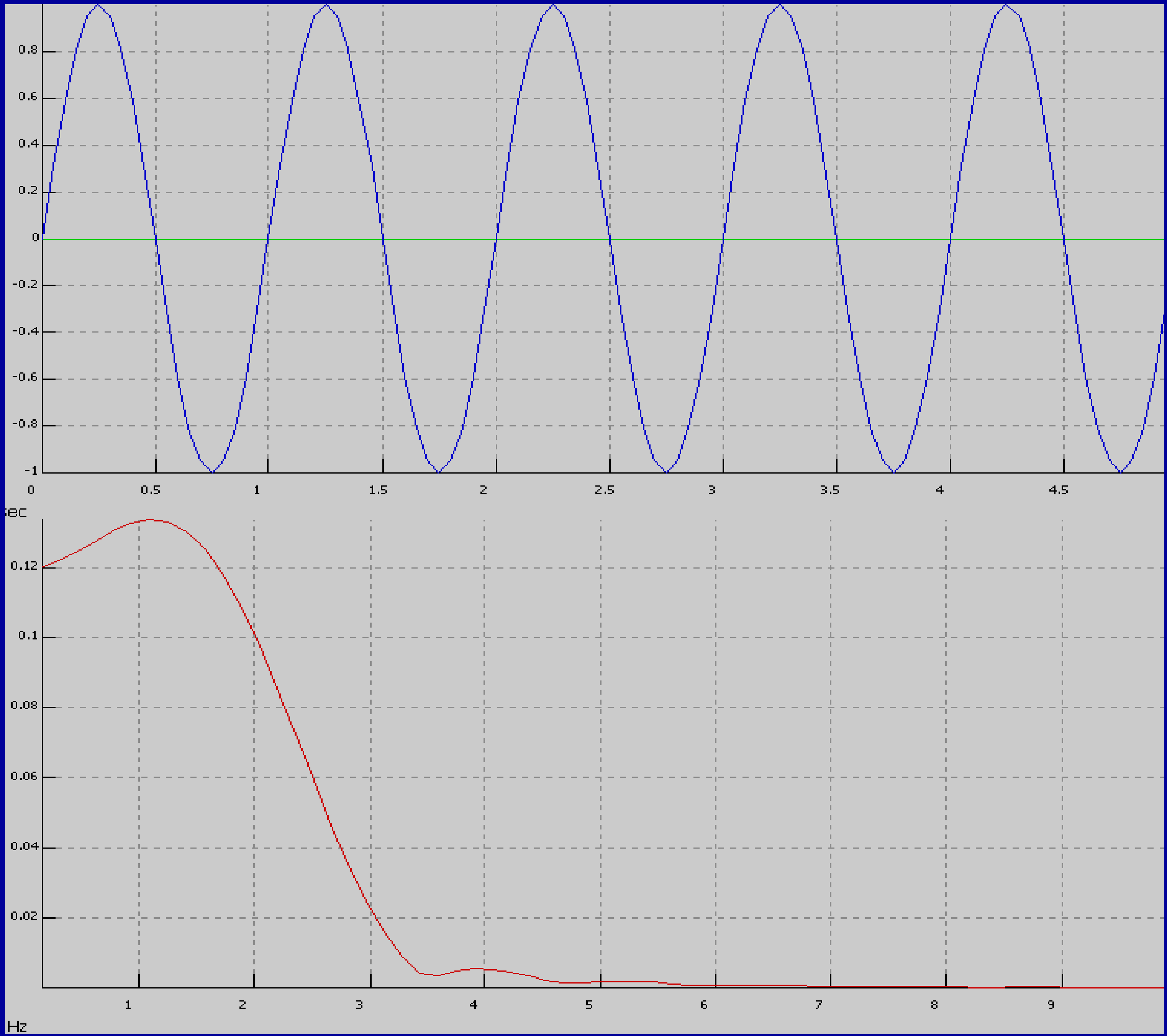
Signal

5 cycles of a 1 Hz sine wave



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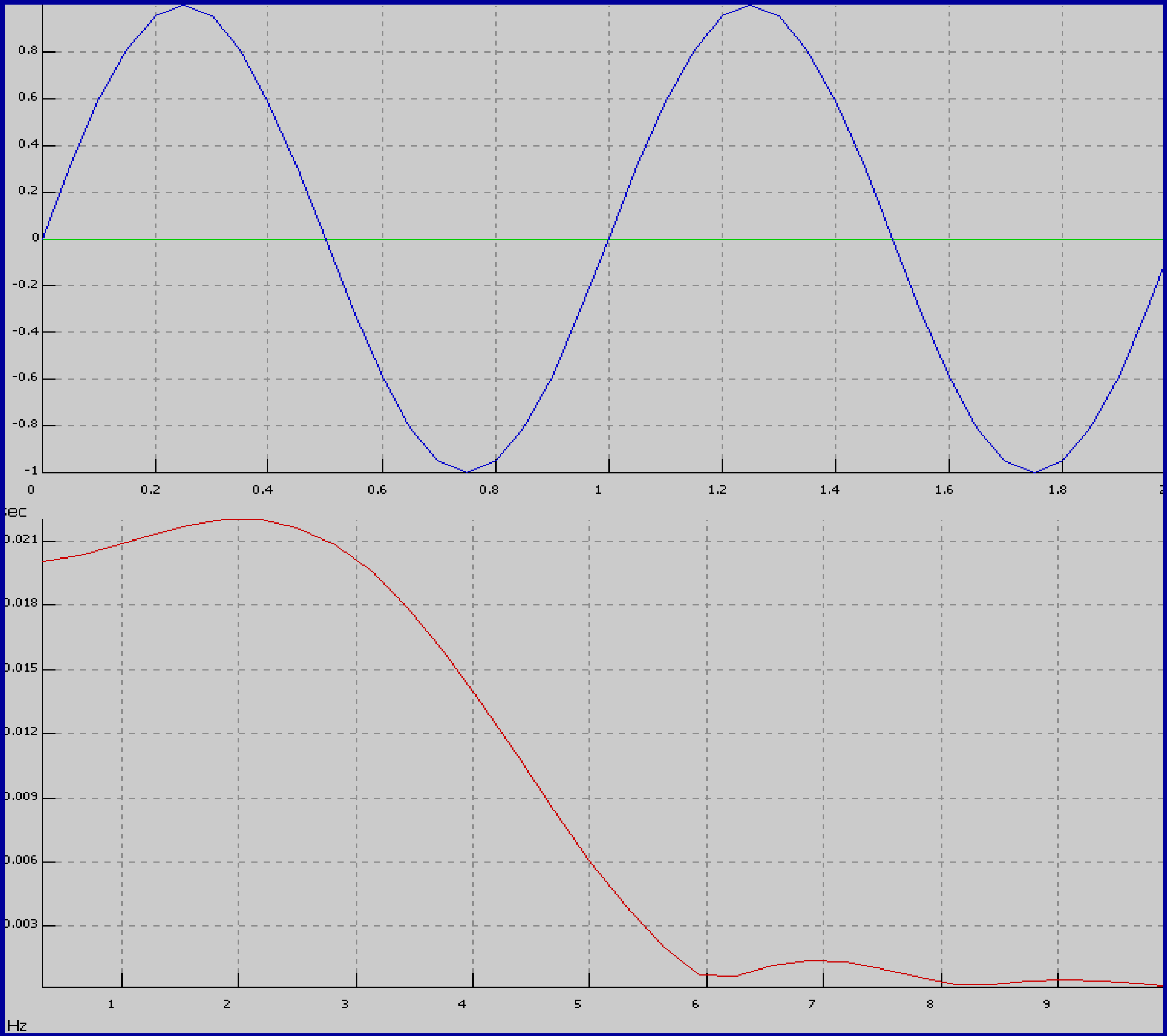
Signal

2 cycles of a 1 Hz sine wave



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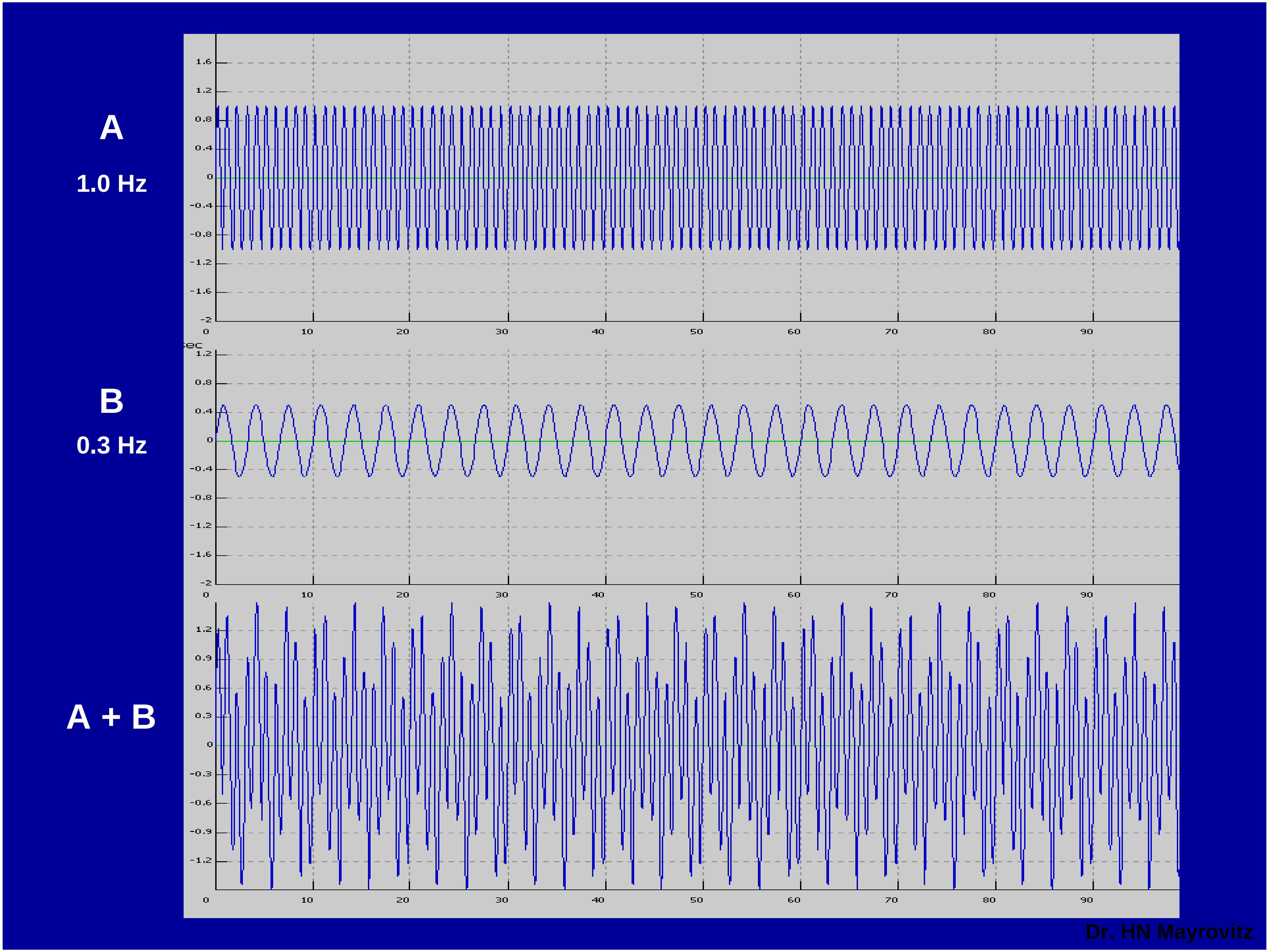
Seperating frequency components requires adequate resolution


A
1.0 Hz
B
0.3 Hz
A + B
sec
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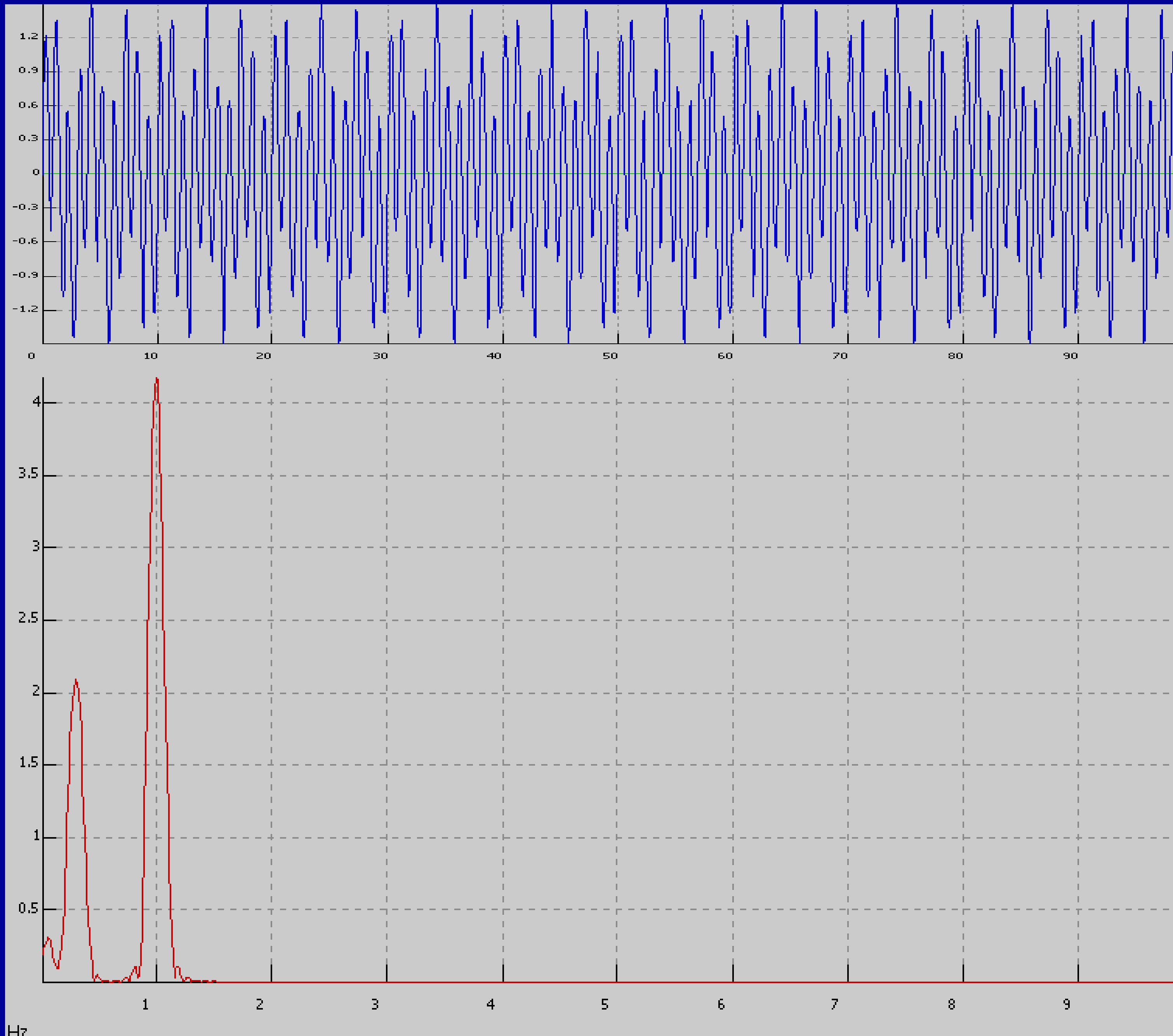
A + B



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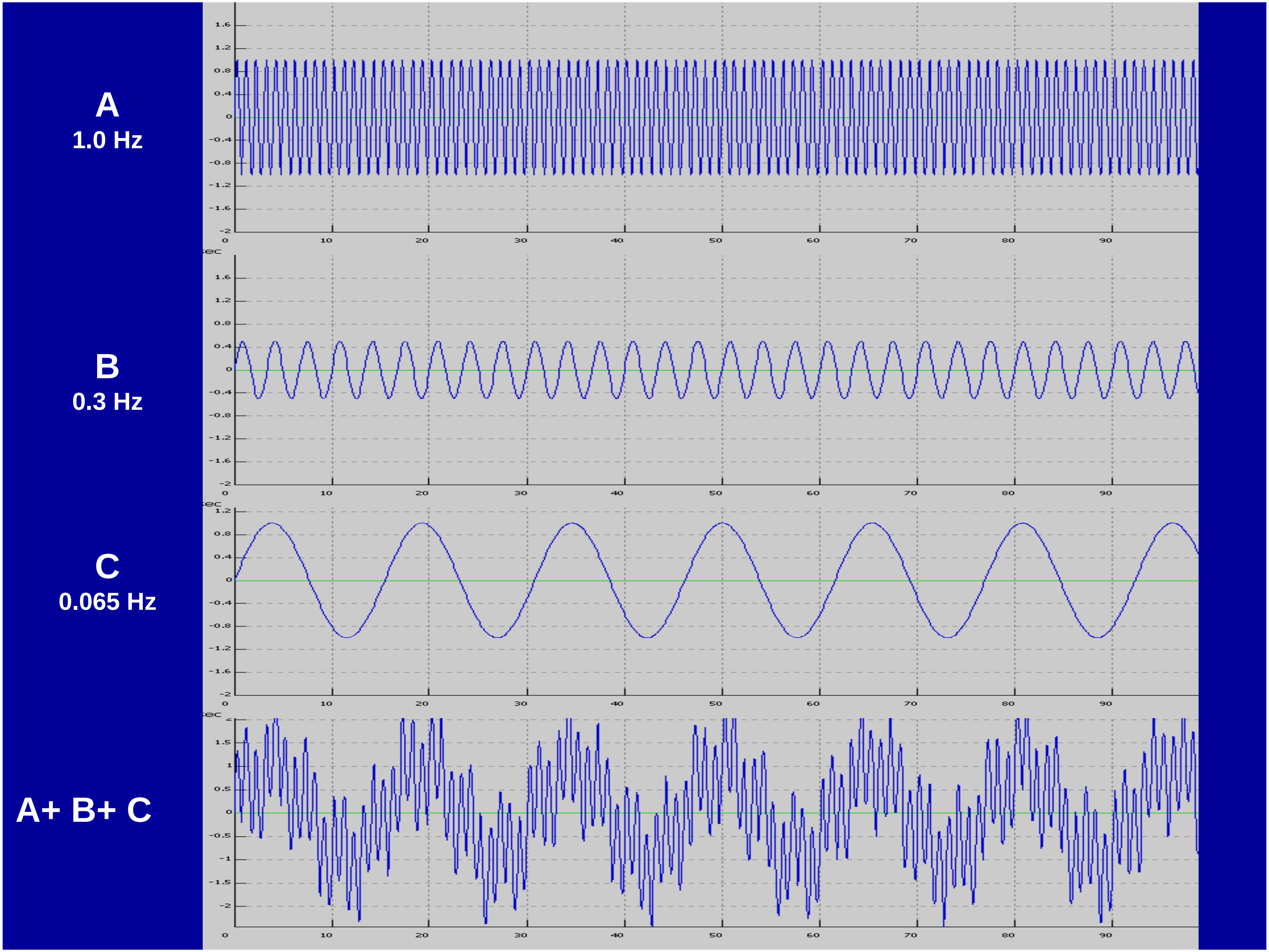
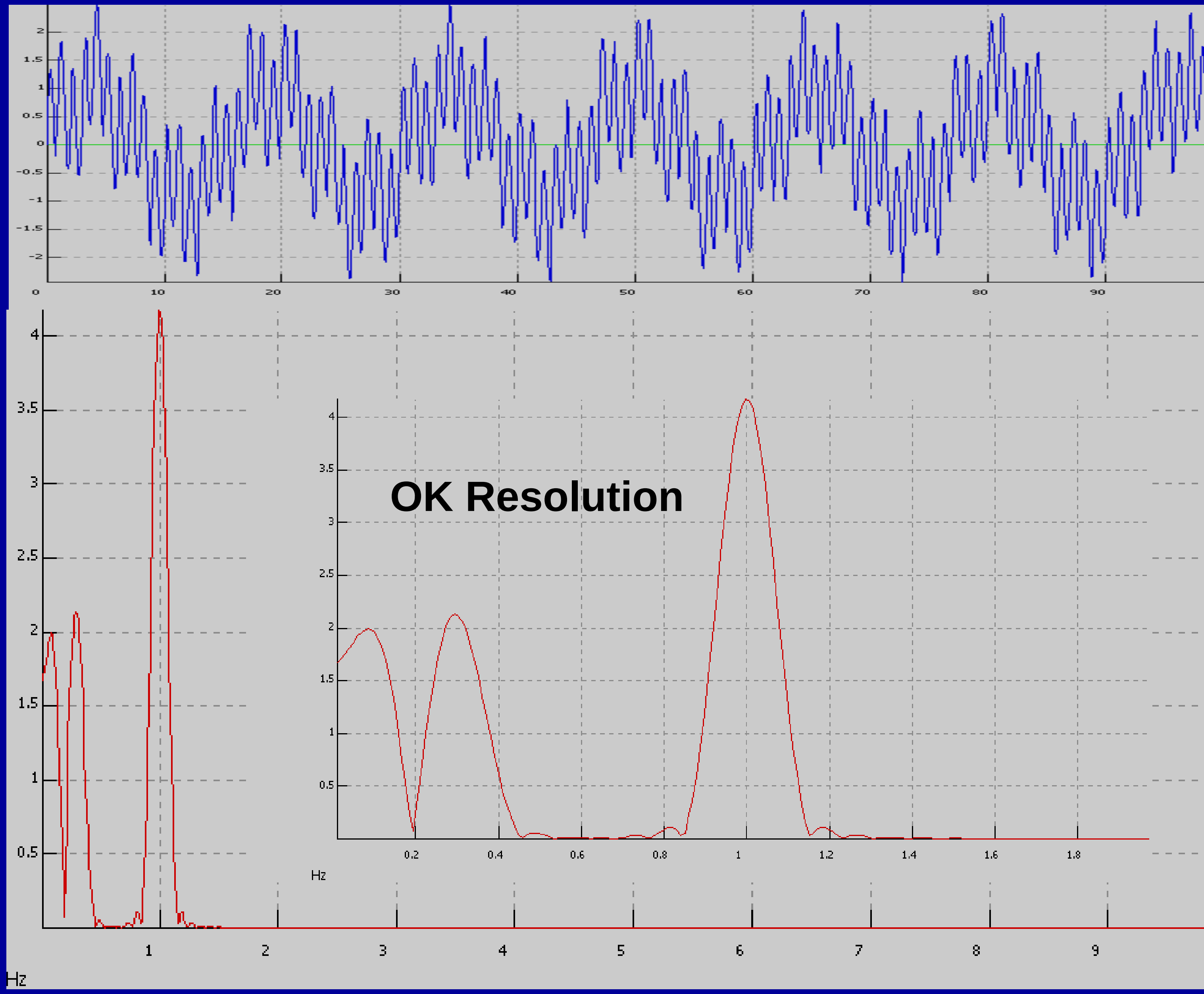

A
1.0 Hz
B
0.3 Hz
C
0.065 Hz
A+ B+ C

A+ B+ C

100 sec



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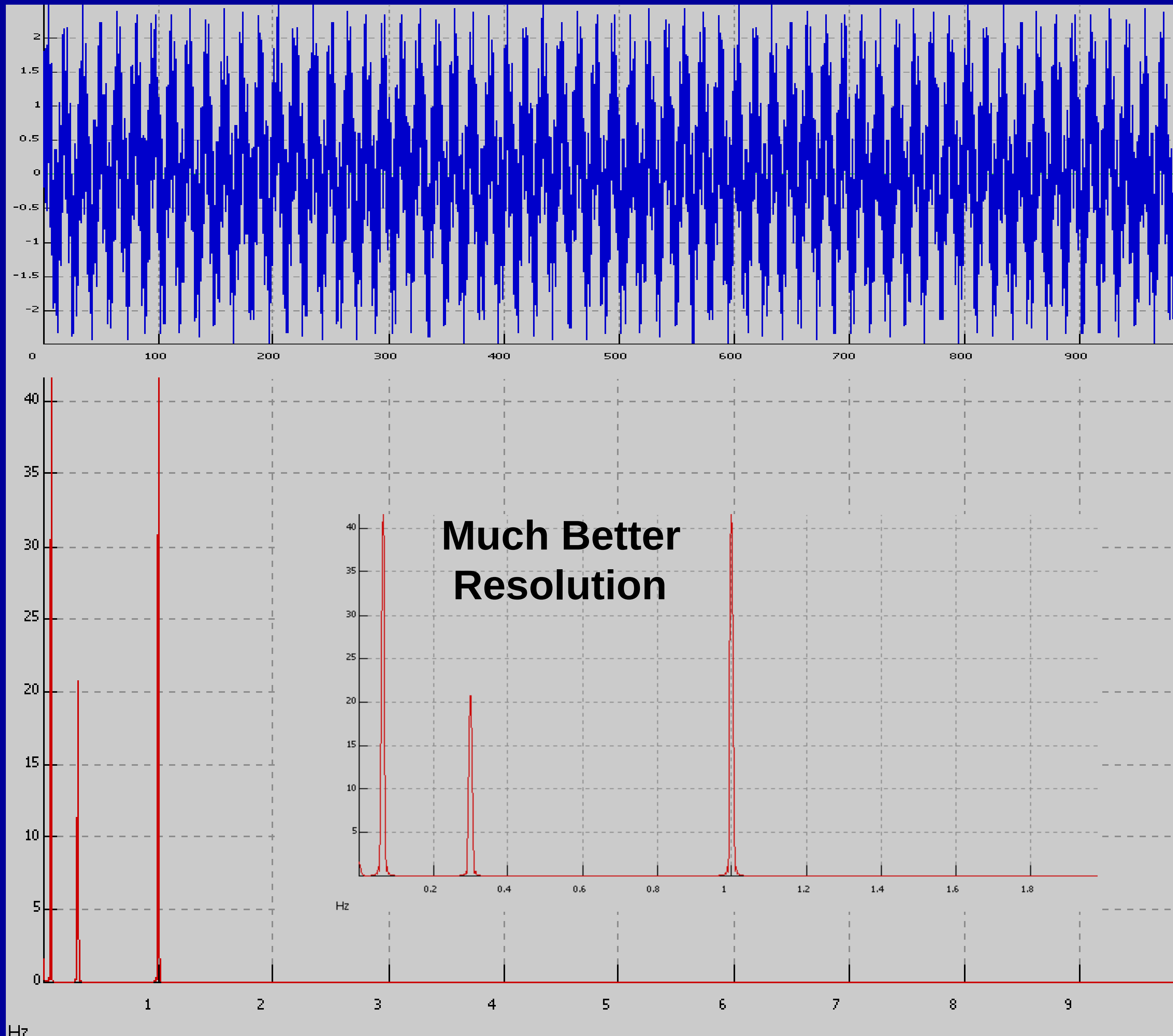
1000 sec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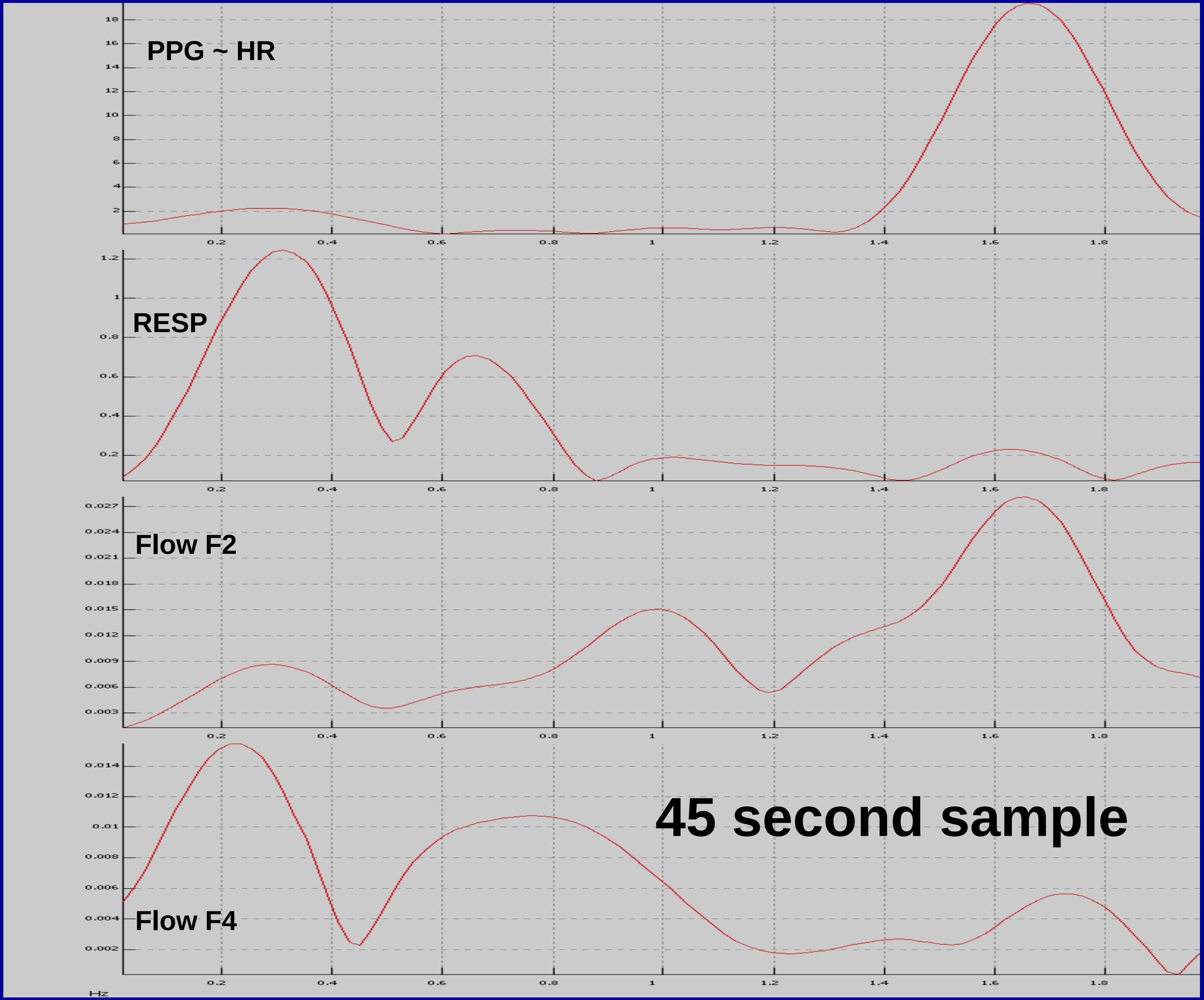
800
900
40
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
Hz
Much Better
Resolution
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Hz



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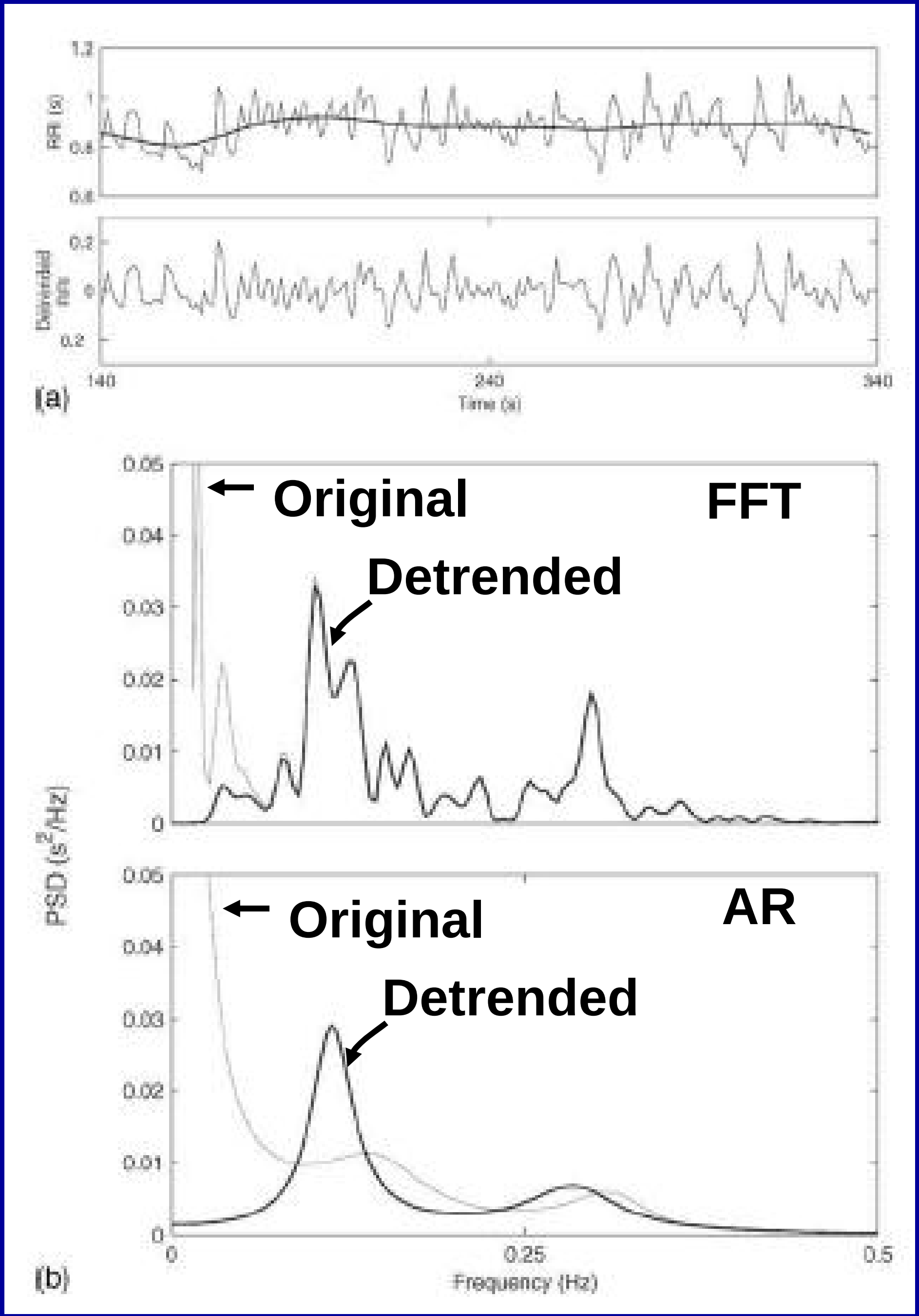
De-Trending

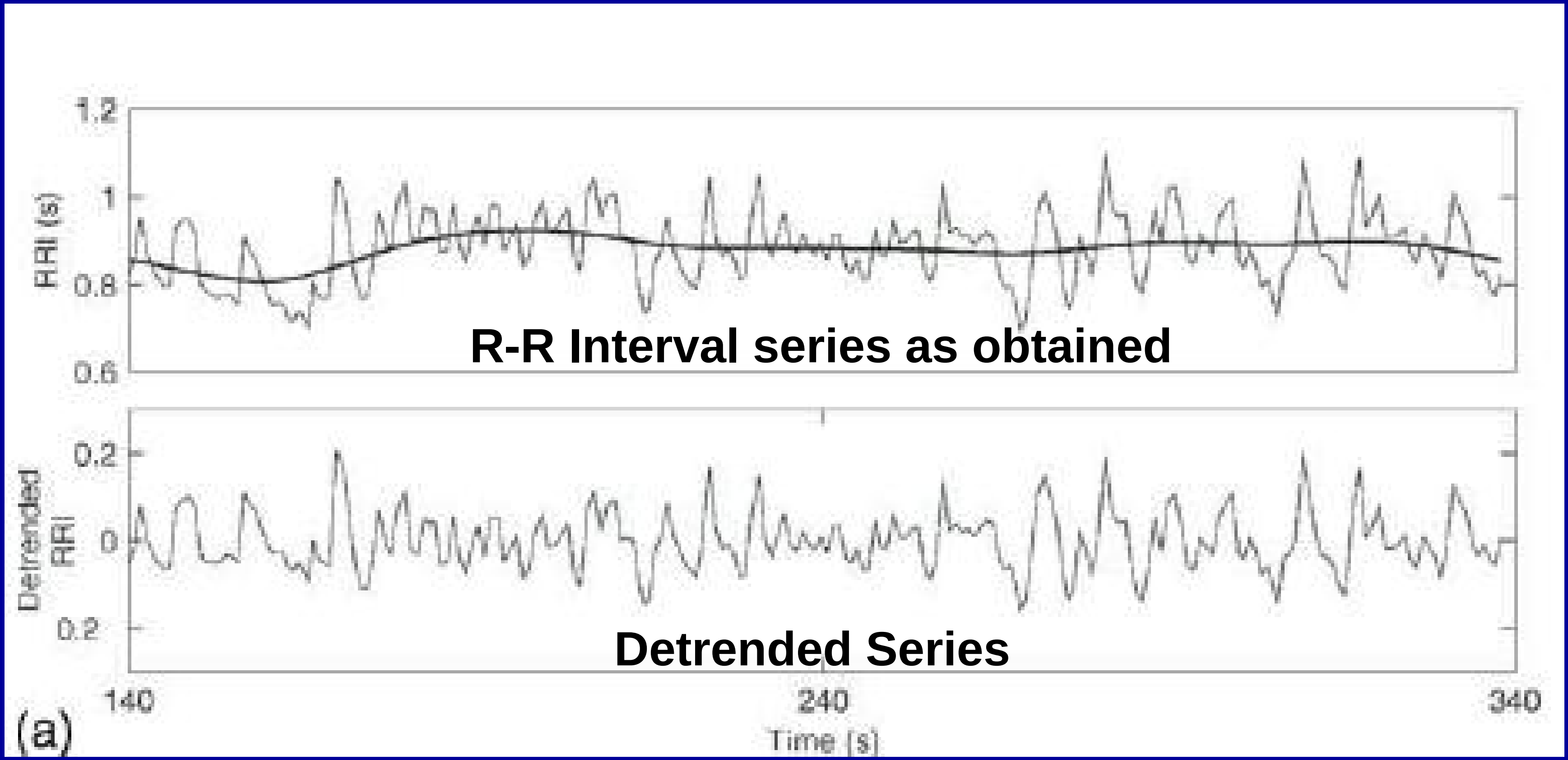
R-R Interval series as obtained

Detrended Series

Power Spectral Density (PSD) of R-R Series



Effect of Detrending

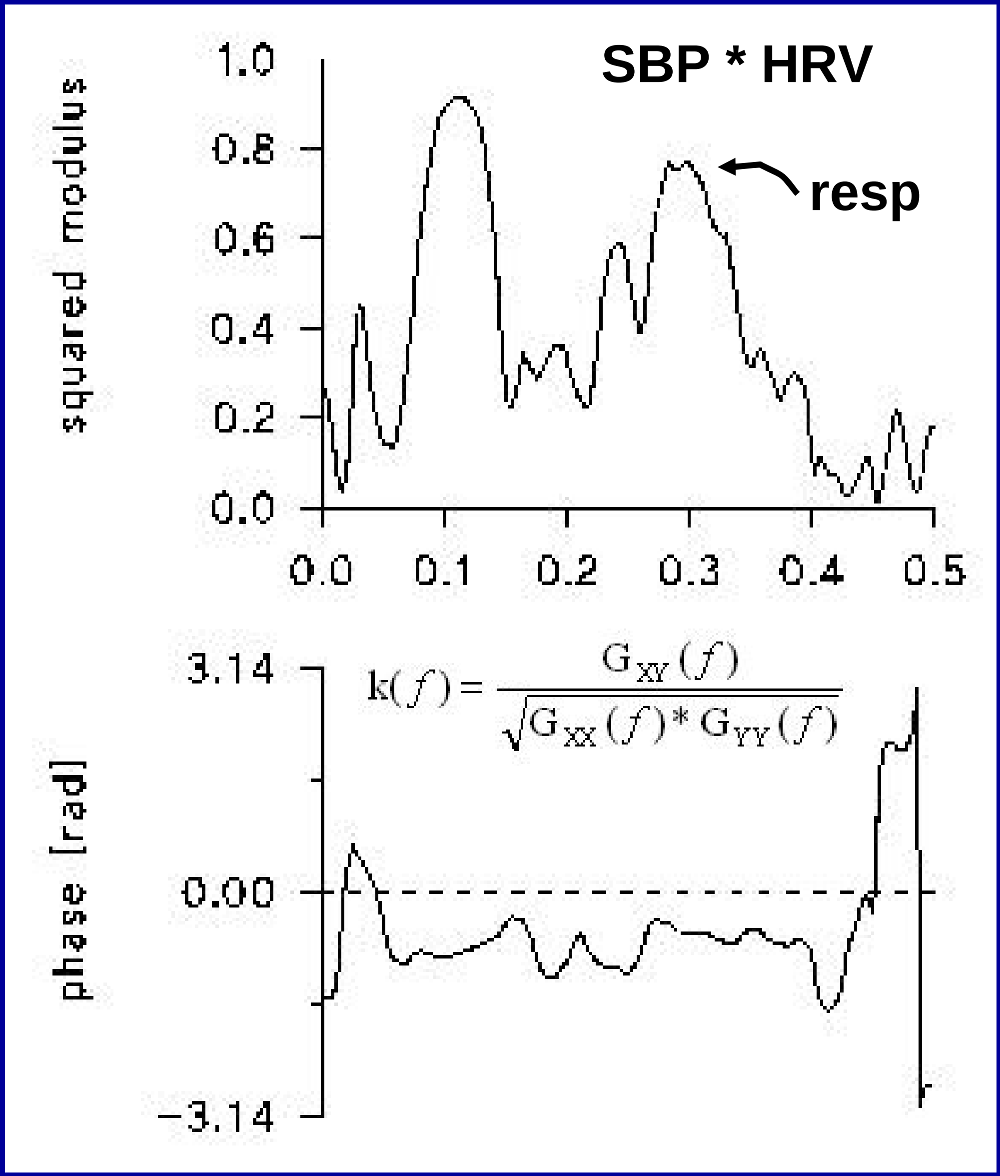


Basic Definitions

Coherence Function - Degree of linear correlation as fn of frequency

Gxx, Gyy and Gxy are spectra of x(t), y(t) and crosspectrum of x and y

$[K(f)]^2$



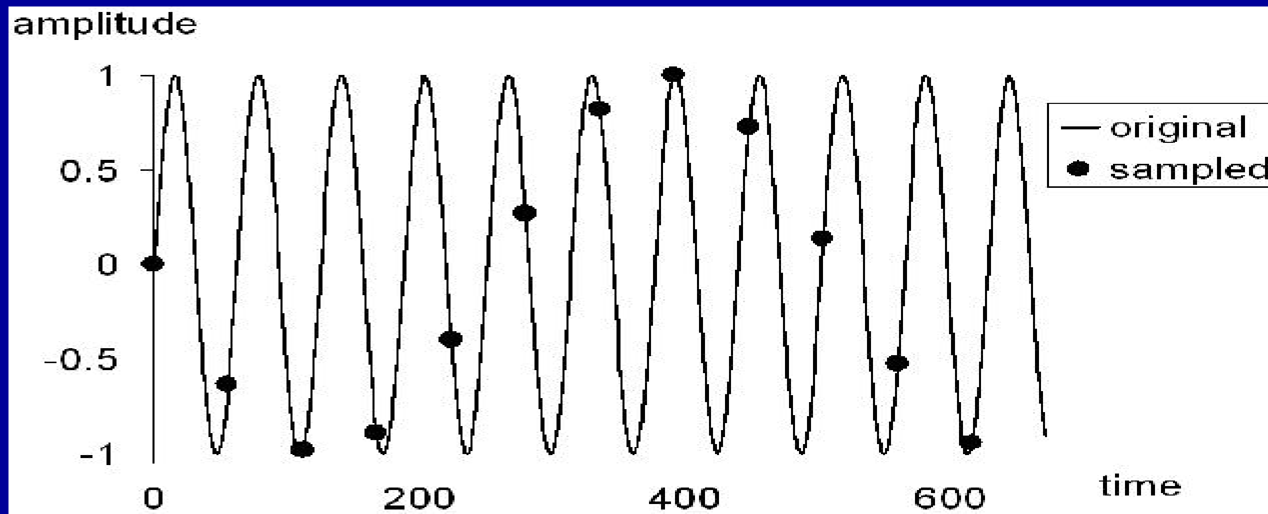
If $x(k)$ is the k-th value of a time series of N samples with sampling period Δt, its energy E is defined as:

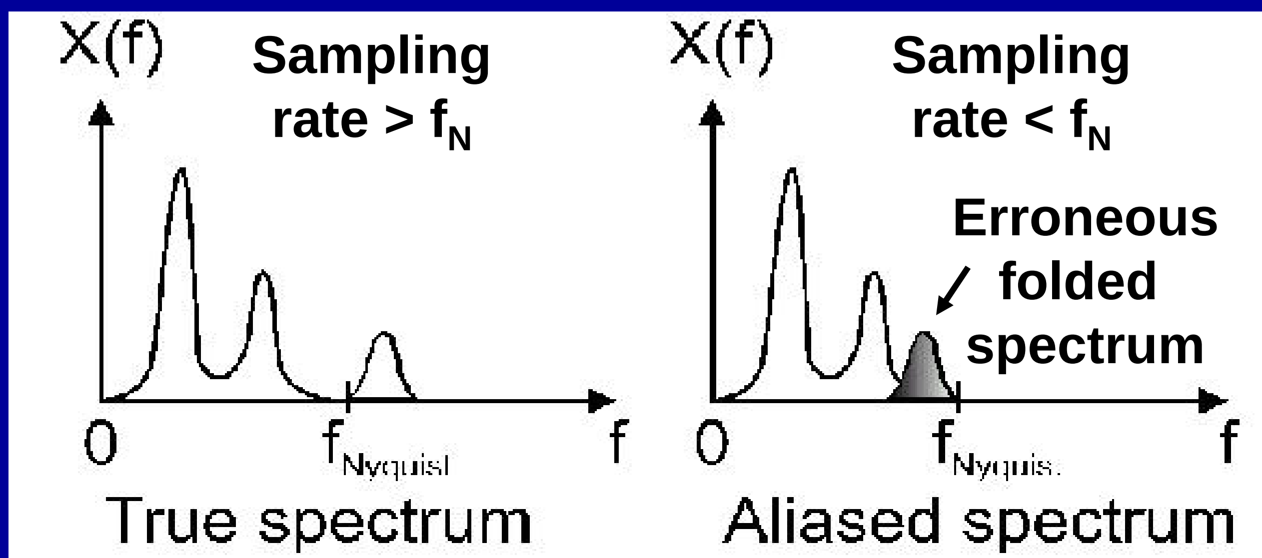
$$E = \sum_{k=0}^{N-1} |x(k)|^2 \Delta t$$

$$P = \frac{E}{N\Delta t} = \frac{1}{N} \sum_{k=0}^{N-1} |x(k)|^2$$

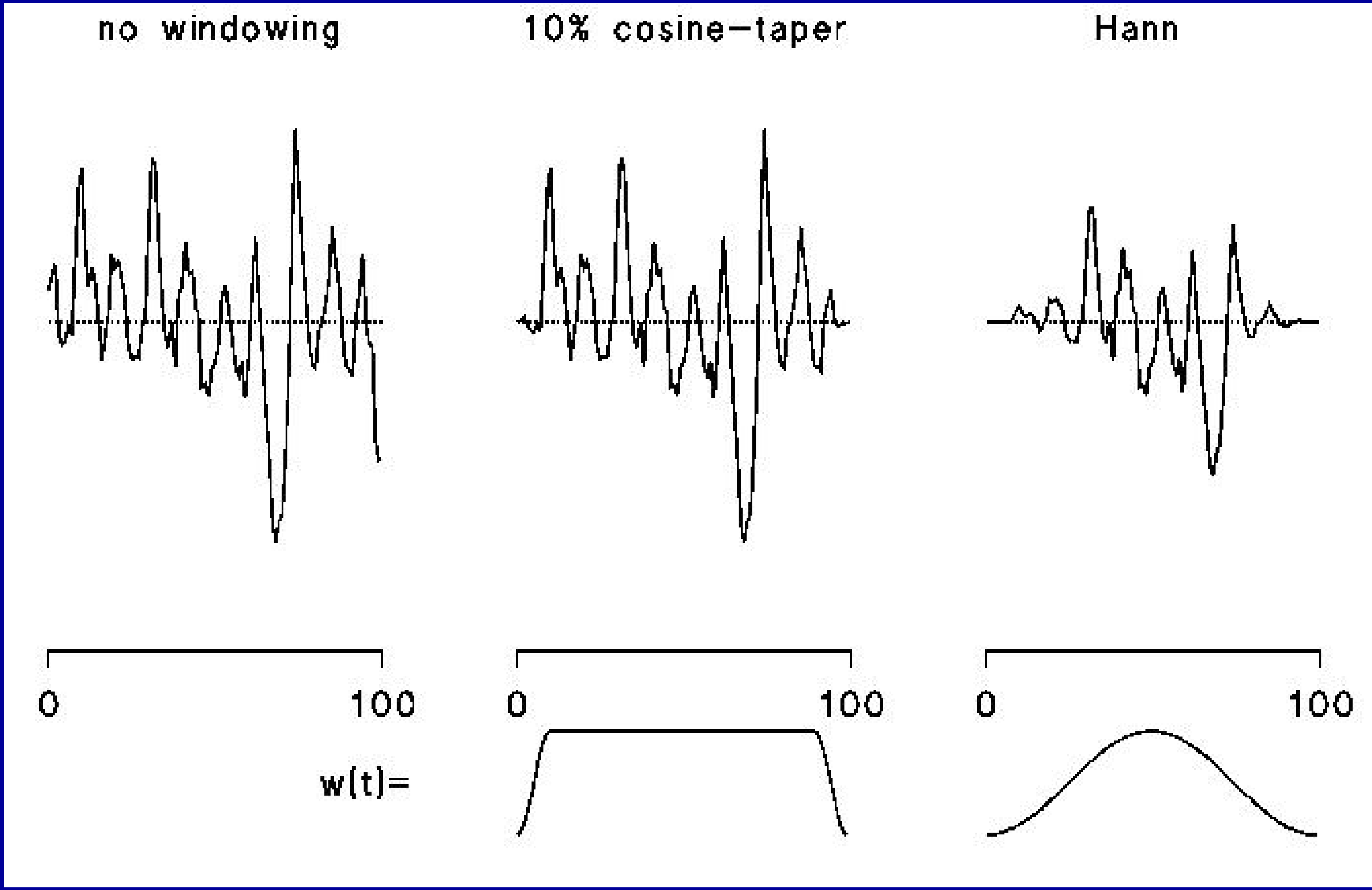
For zero-mean time series, the power is equal to the variance of the sample of the N values $x(k)$.

Aliasing Artifacts





Windowing



Autocorrelation Function

Measure of the dependence of time series values at one time on the values at another time.

Given the time series x(*n*), *n*=1, 2, ...N, the autocorrelation function at lag *k* is defined as:

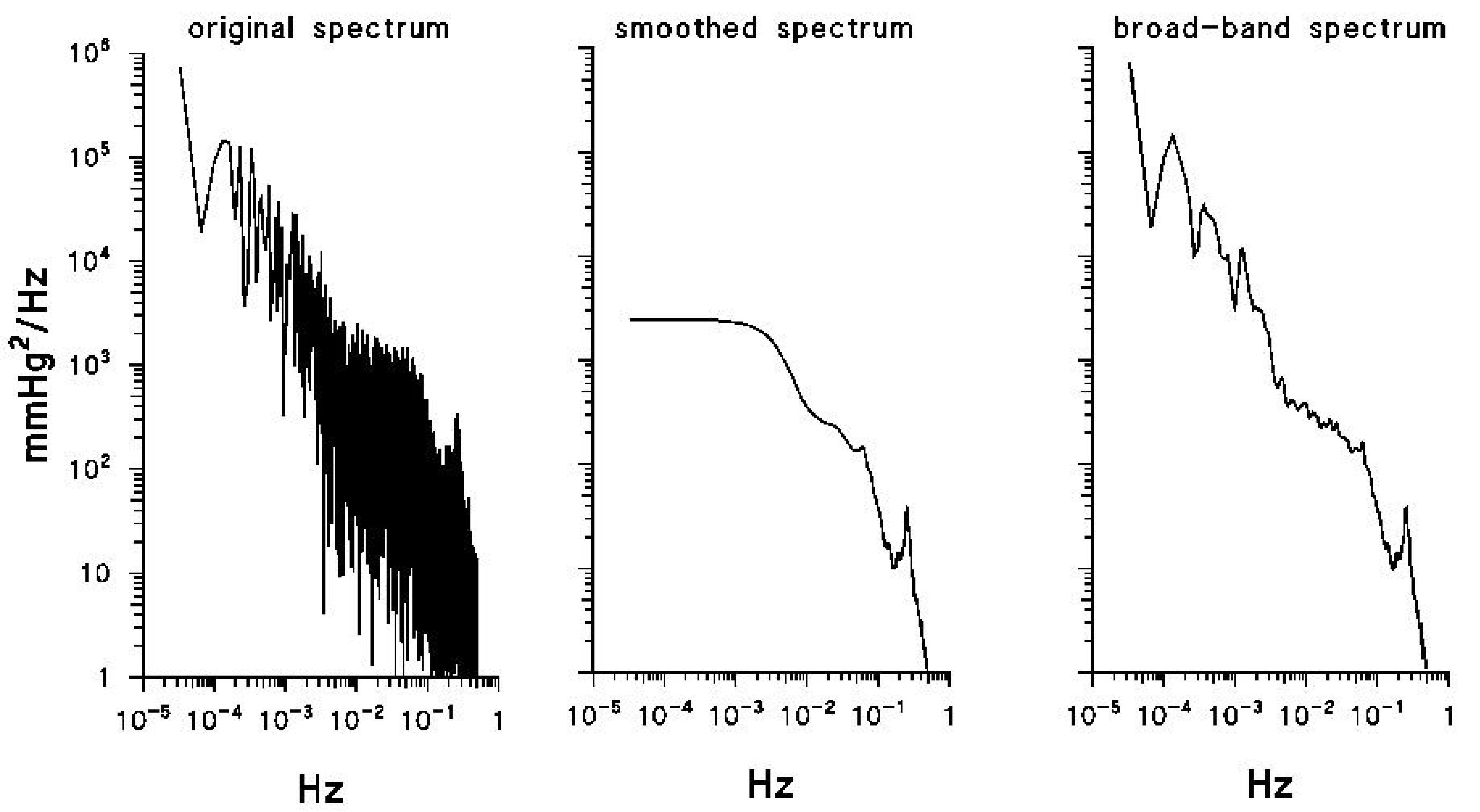
$$R_{xx}(k) = \frac{1}{N-k}\sum_{n=1}^{N-k} x(n)x(n+k)$$

The value of the autocorrelation function at lag 0 is the power of x(*n*), or its variance if the mean value of x(*n*) is zero:

$$R_{xx}(0) = \frac{1}{N-k}\sum_{n=1}^{N-k} x(n)^2$$

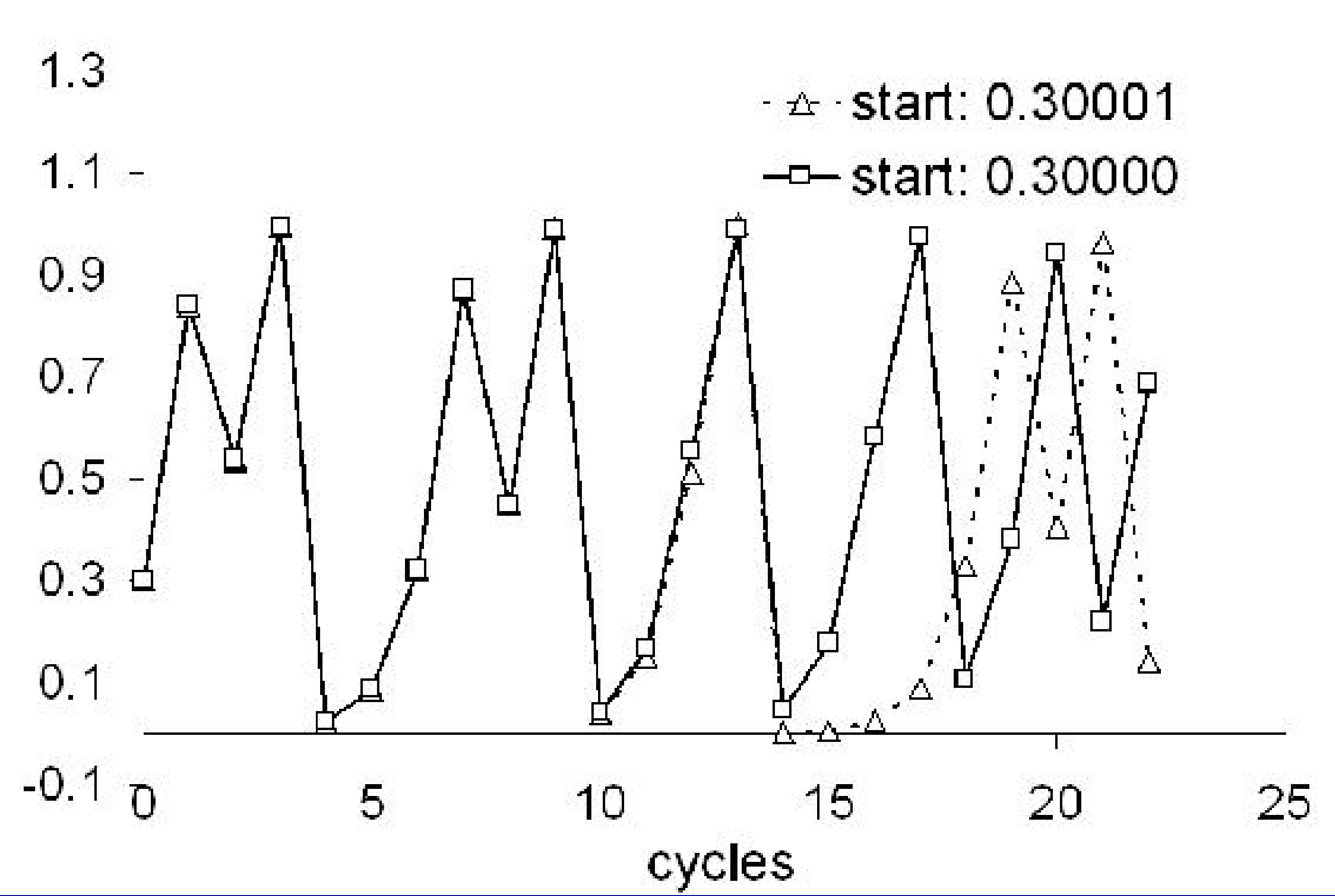
Moreover, $\sqrt{R_{xx}(\infty)}$ is the mean value for random processes.

Broad Band Smoothing

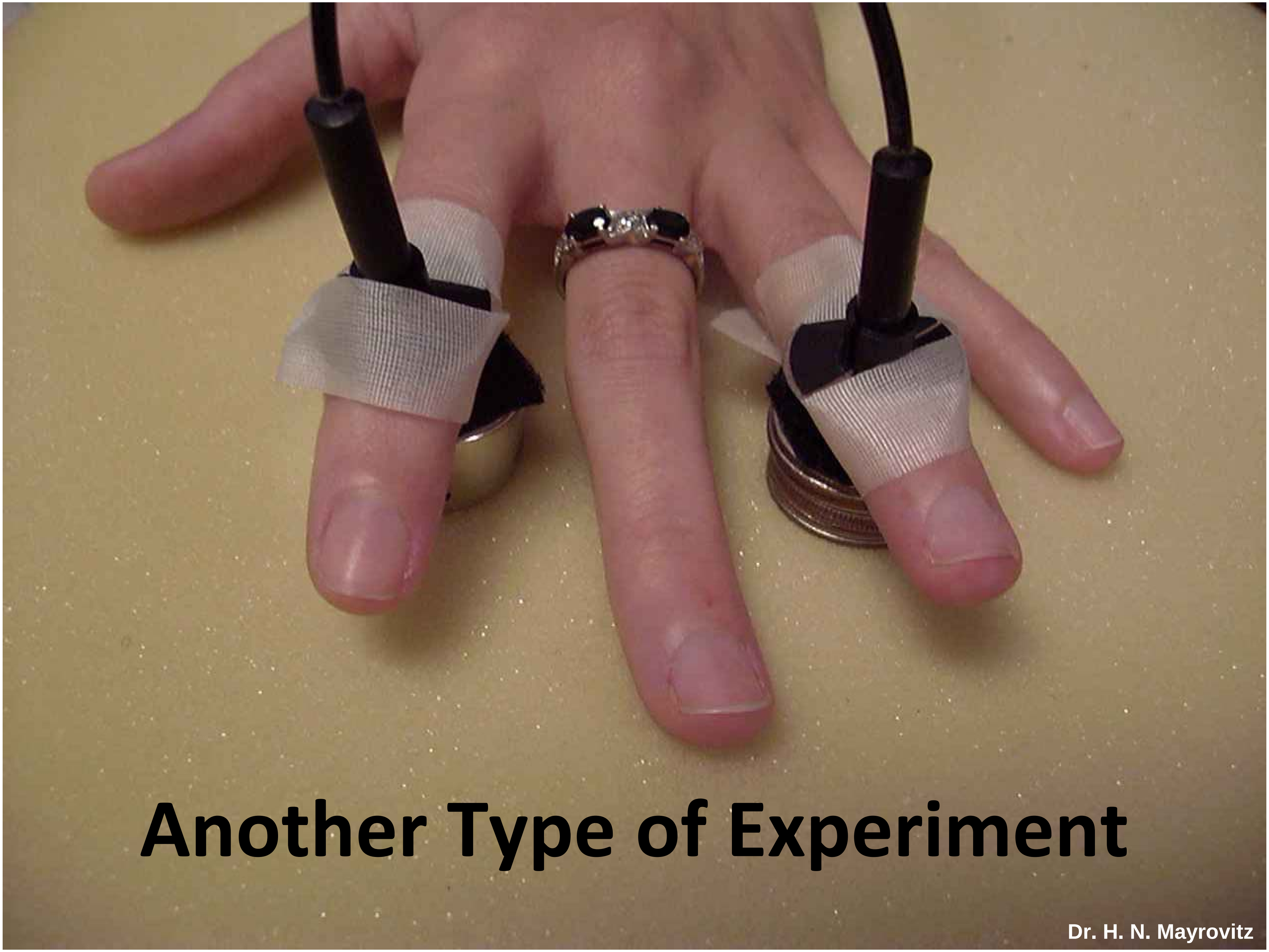


Left: unsmoothed FFT spectrum of blood pressure from a 8-h recording: this spectrum is characterized by a very high frequency resolution, but also by a very high estimation variance. Centre: the same spectrum smoothed by a moving average filter of order 250 (i.e., average over 250 adjacent spectral lines). Estimation variance is largely reduced, but the frequency resolution dramatically worsens and important spectral details may be lost at the lower frequencies. Right: broad-band spectrum obtained from the raw FFT spectrum by averaging adjacent spectral lines: in this case the number of lines to average increases with the frequency from 1 to 250. The desired reduction of the estimation variance is obtained at the highest frequencies preserving the original frequency resolution at the lowest frequencies.

Chaos



Sensitivity to initial conditions. Small changes in initial conditions lead to totally different behaviour patterns after a certain time (here 14 cycles). This sensitivity to initial conditions may be quantified by means of the largest Lyapunov exponent.


Another Type of Experiment
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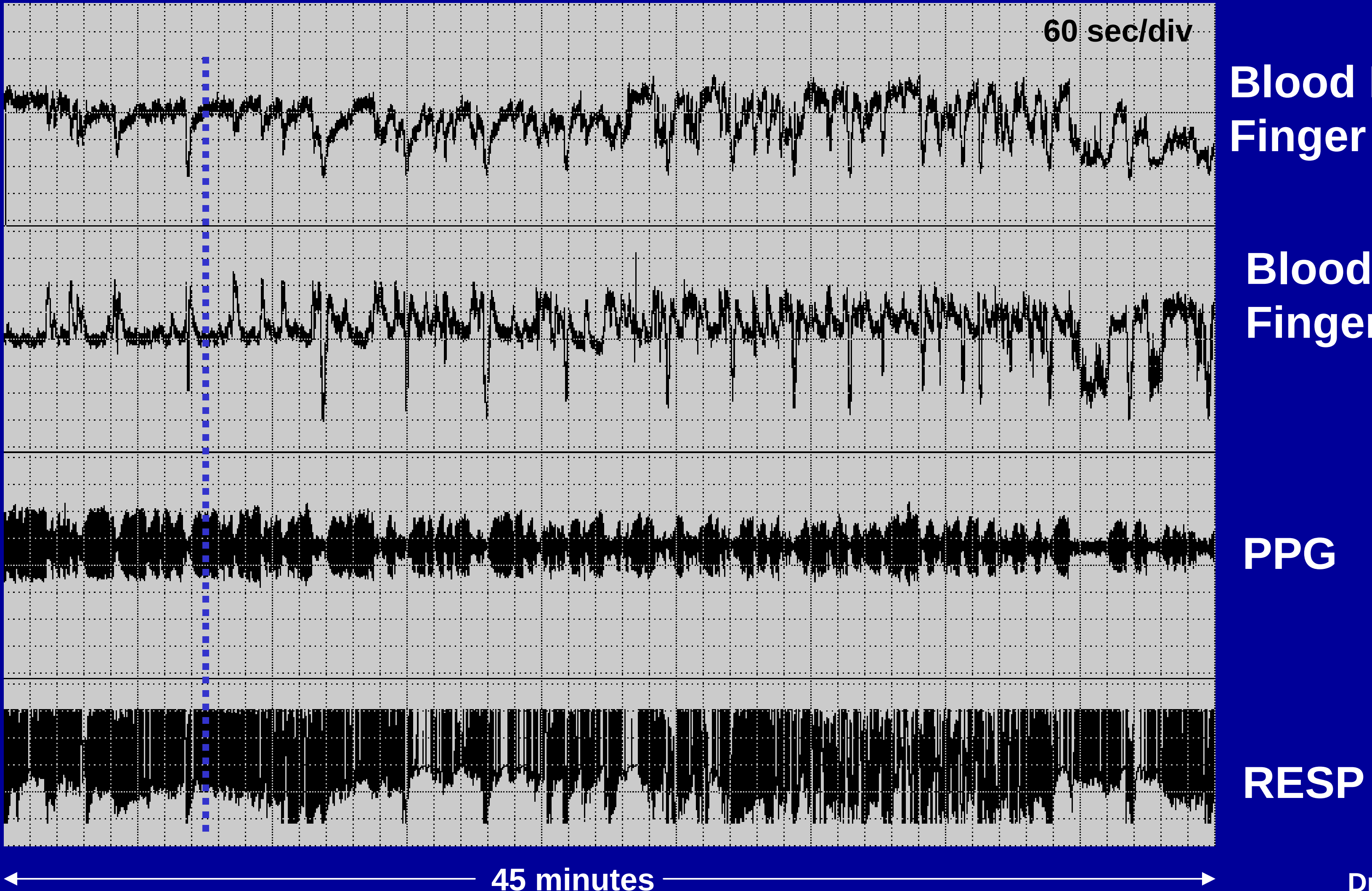
Experiment



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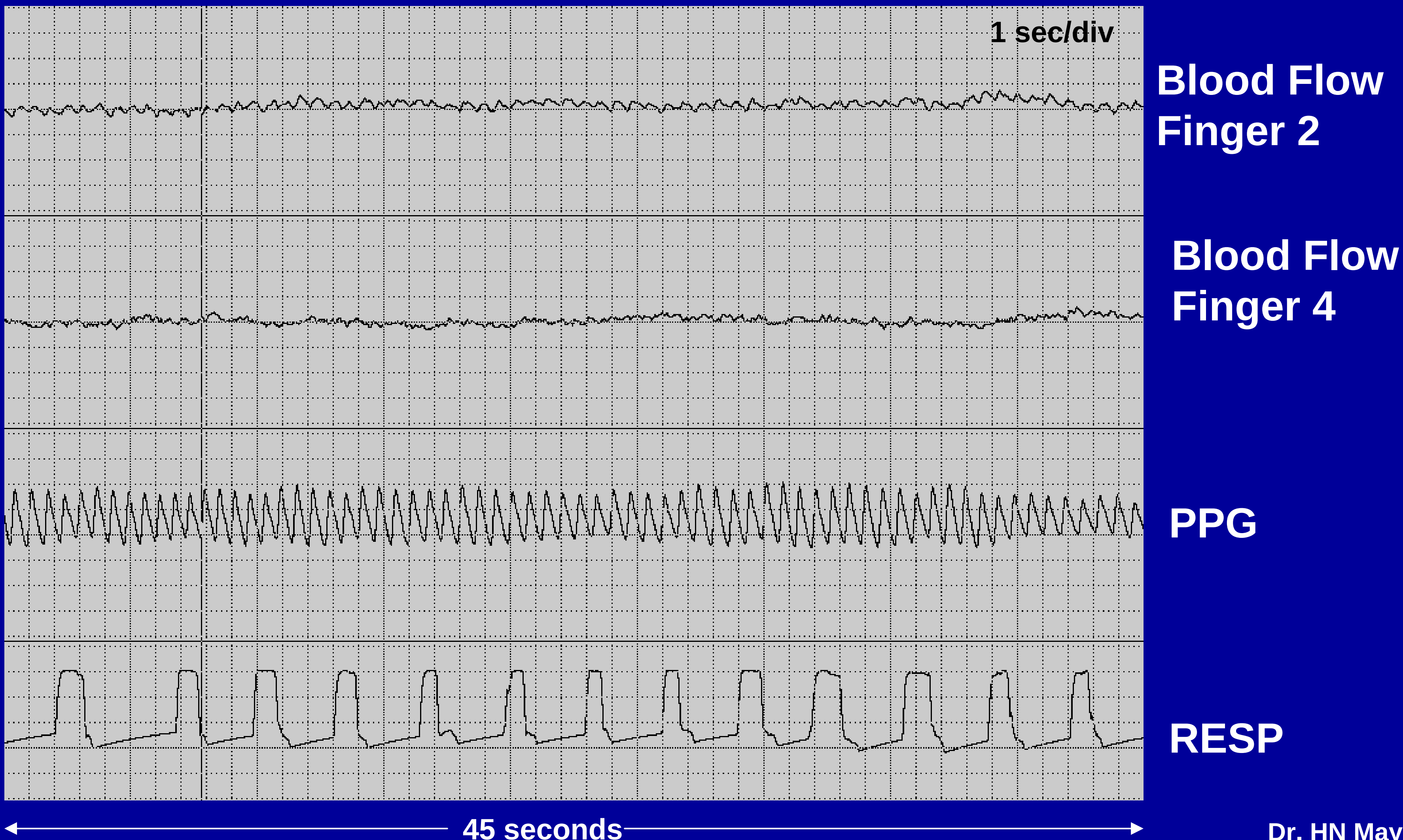
Experiment



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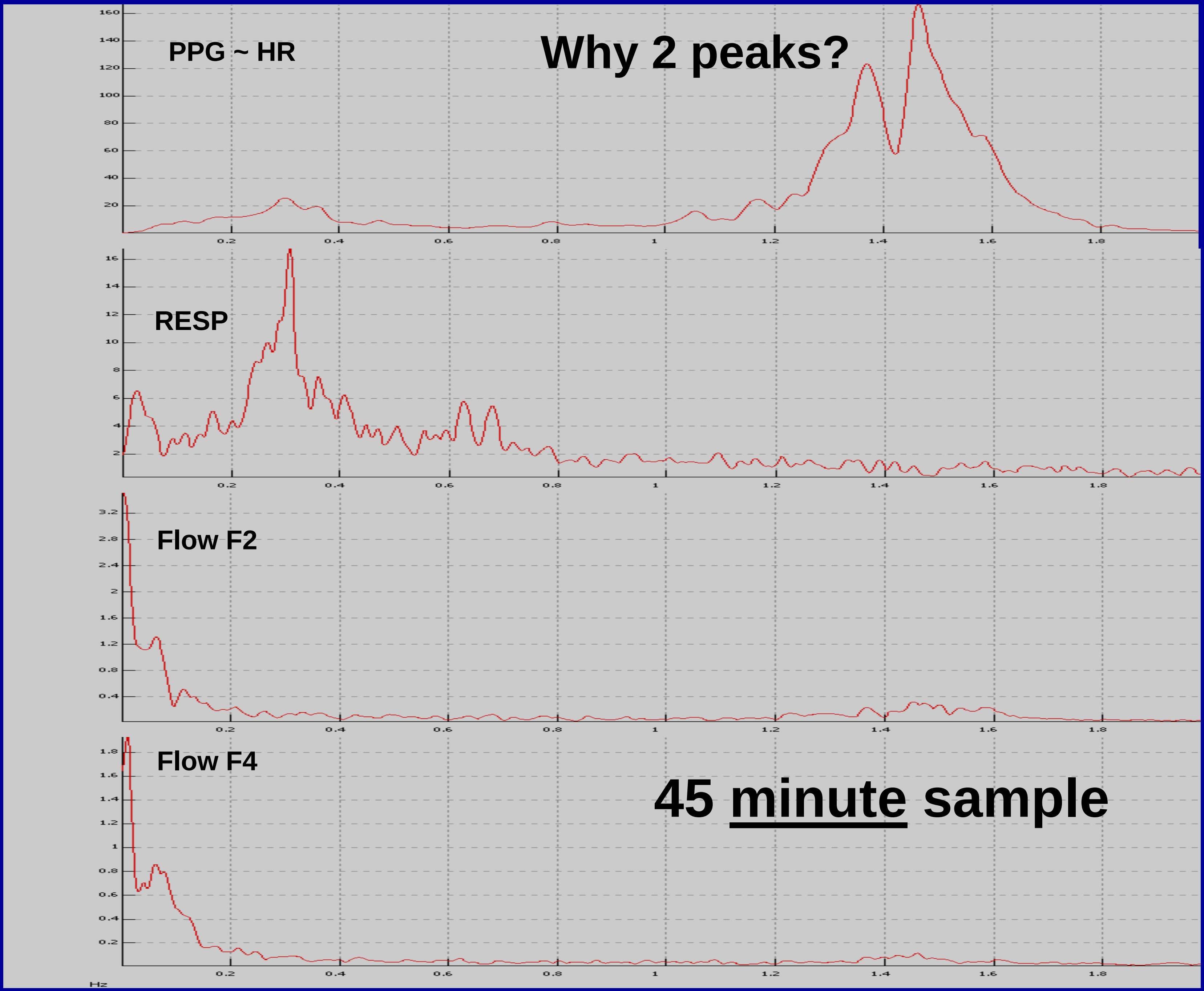

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Physiological signals whose spectral content changes with time

Principle of STFT
Short Time Fourier Transform

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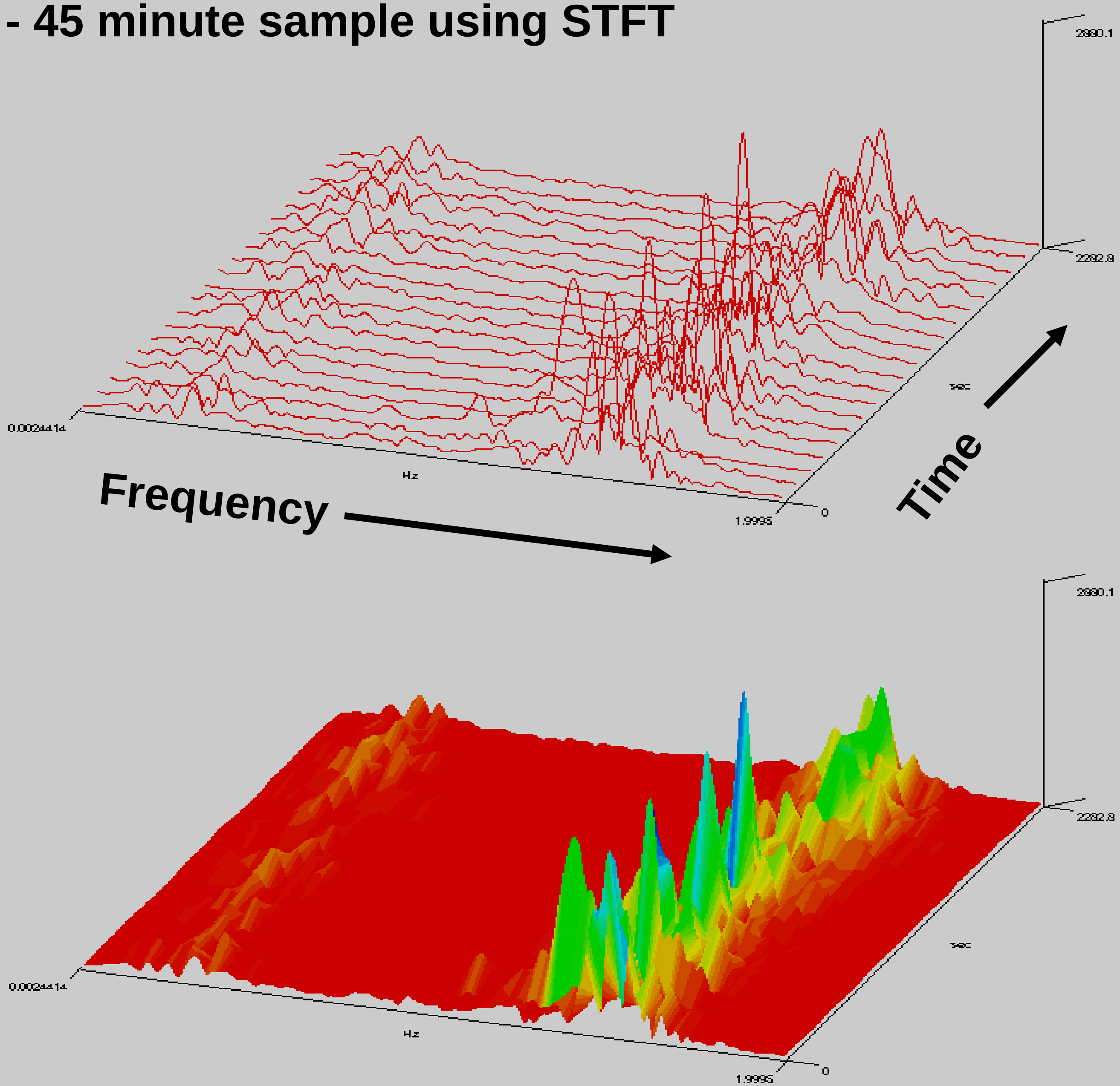
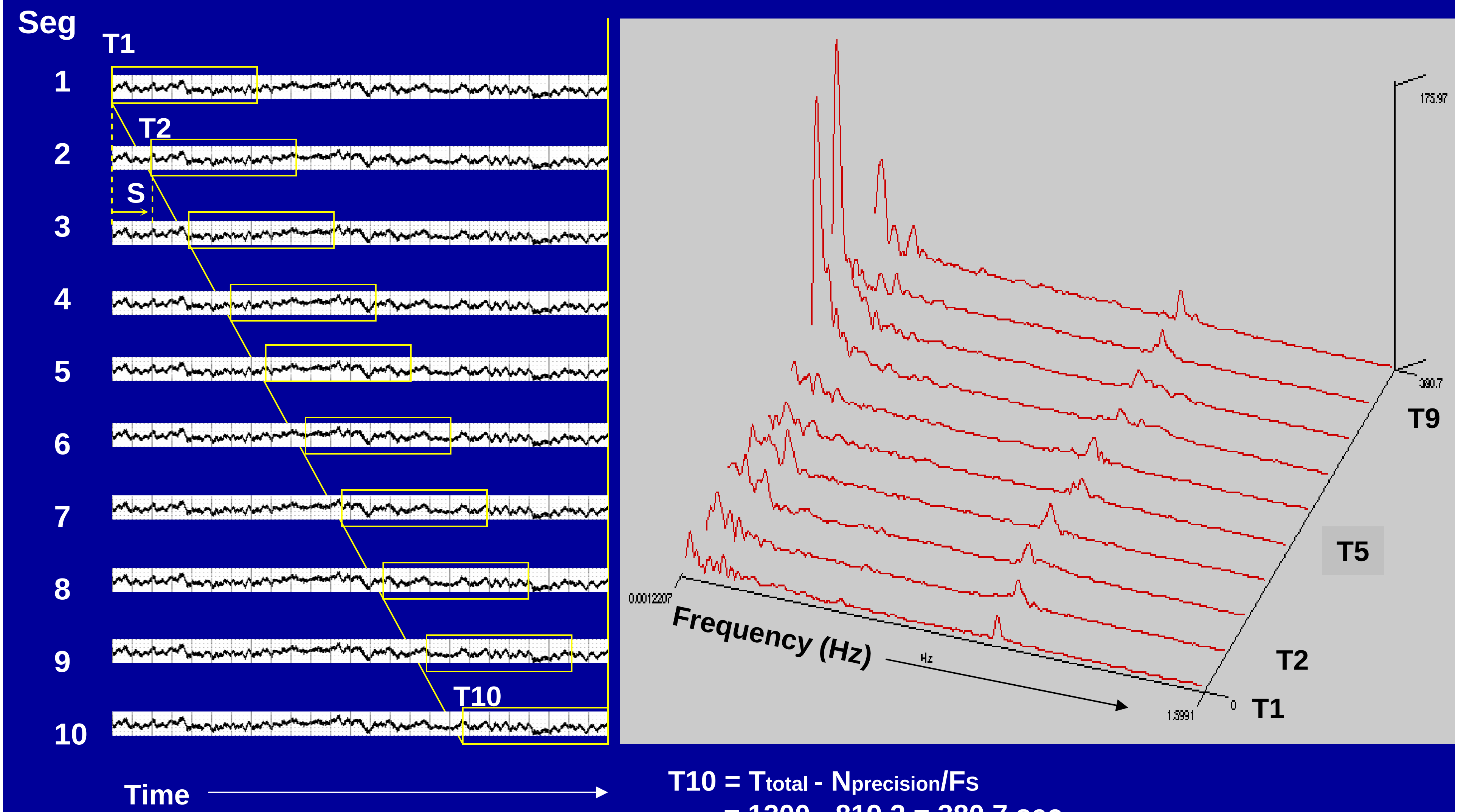
PPG - 45 minute sample using STFT



Principles of Short Time Fourier Transform Analysis



$T10 = T_{total} - N_{precision}/F_S$
$= 1200 - 819.2 = 380.7$ sec
$= (N_{segs}-1) \times S = 9 \times 846/20 = 9 \times 42.3$ sec $= 380.7$ sec

T_{total} = 20 minutes =1200 sec, F_S =20 s/sec
$N_{precision}$ = 16384 = 16384/20 = 819.2 sec
$F_{precision}$=(1/819.2) = 0.0012 Hz

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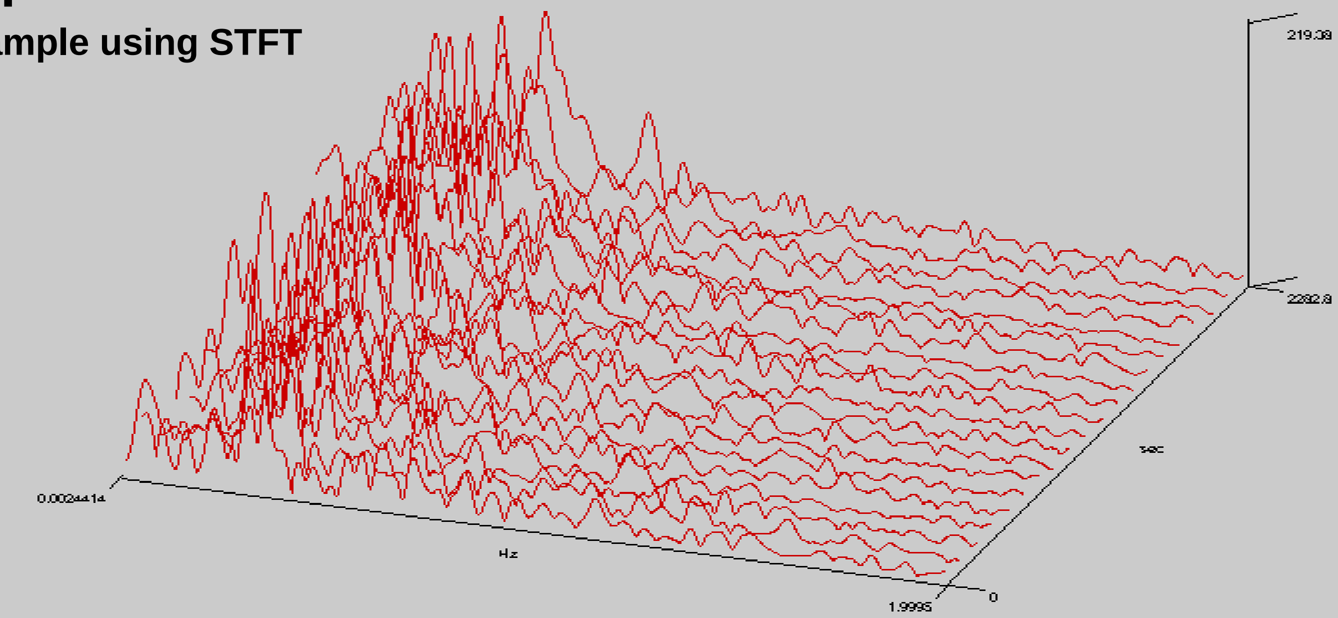
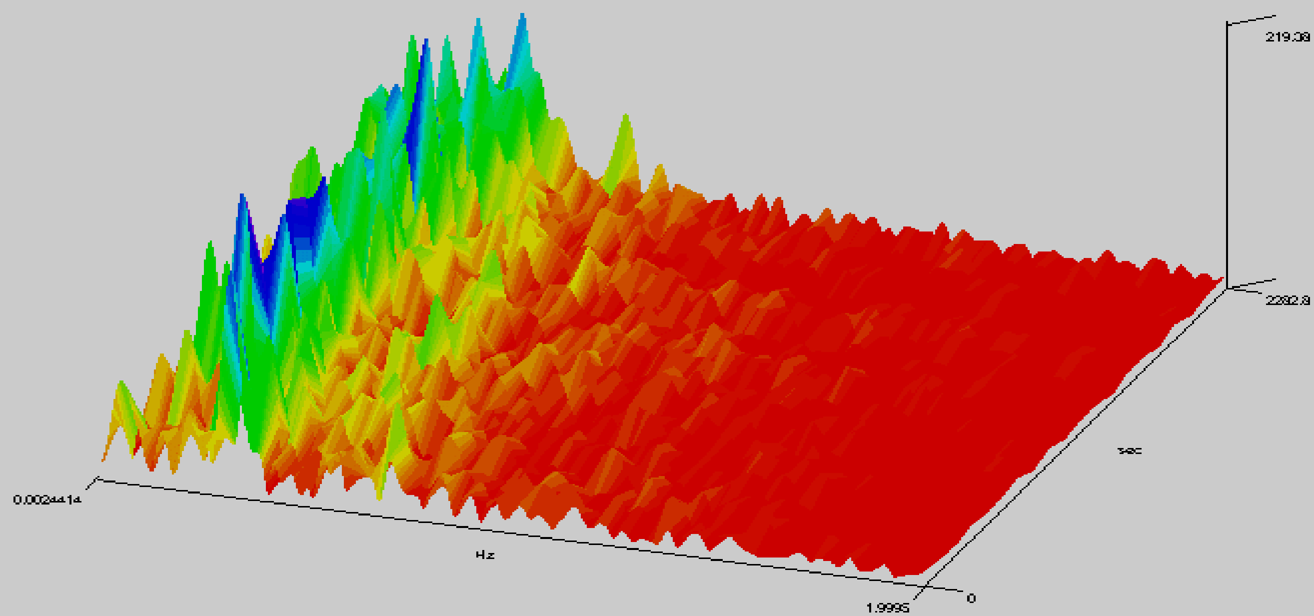
RESP

45” sample using STFT





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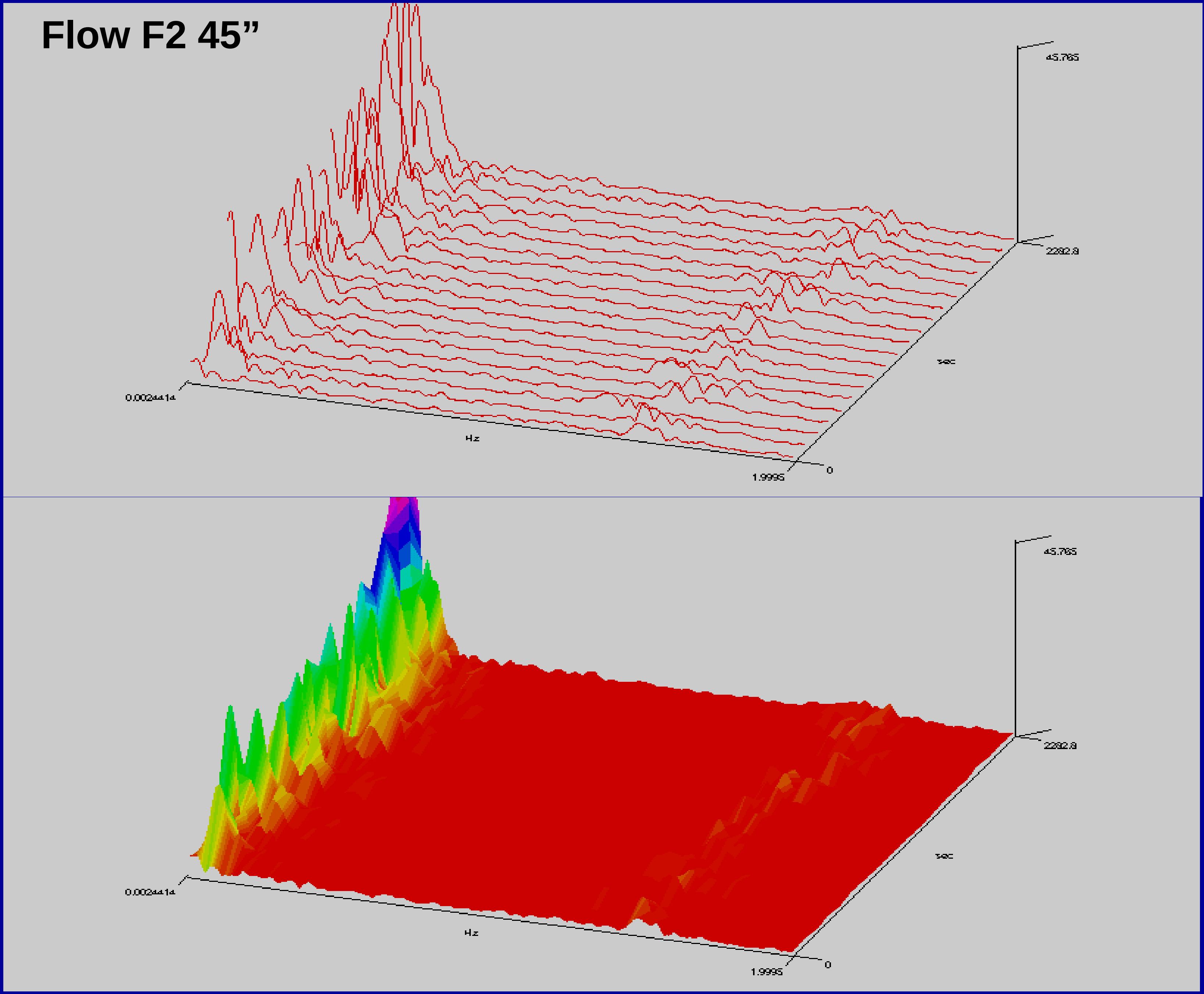
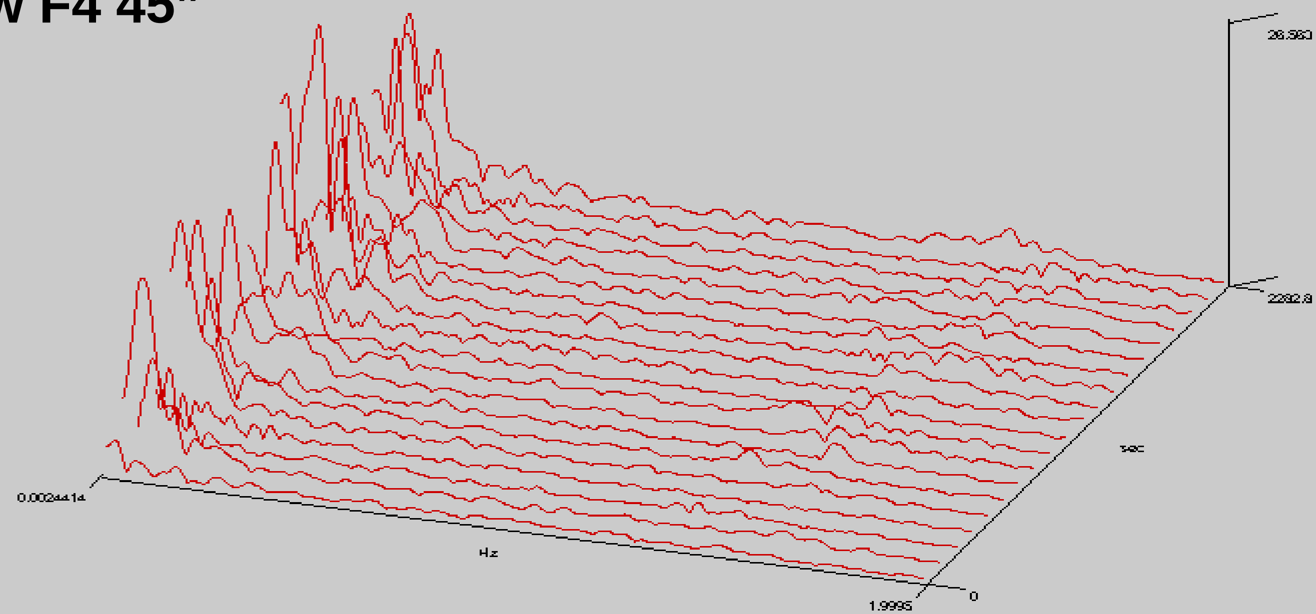
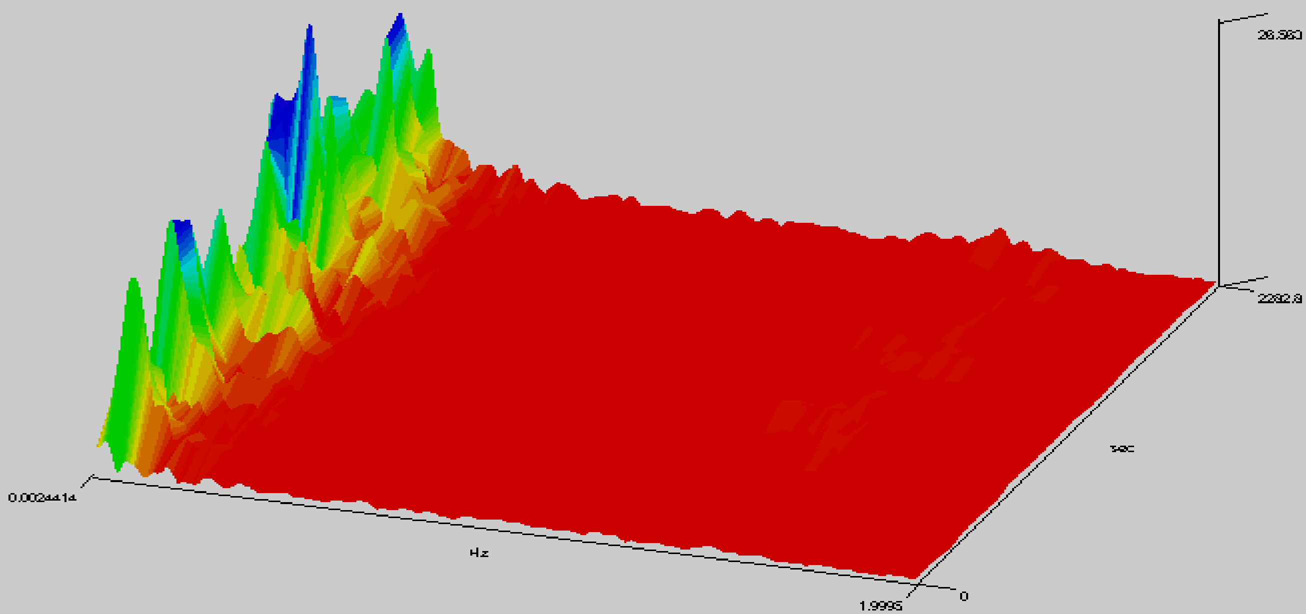
Flow F2 45”


45.765
2282.8
sec
0.0024414
Hz
1.9995
0
45.765
2282.8
sec
0.0024414
Hz
1.9995
0

Flow F4 45”





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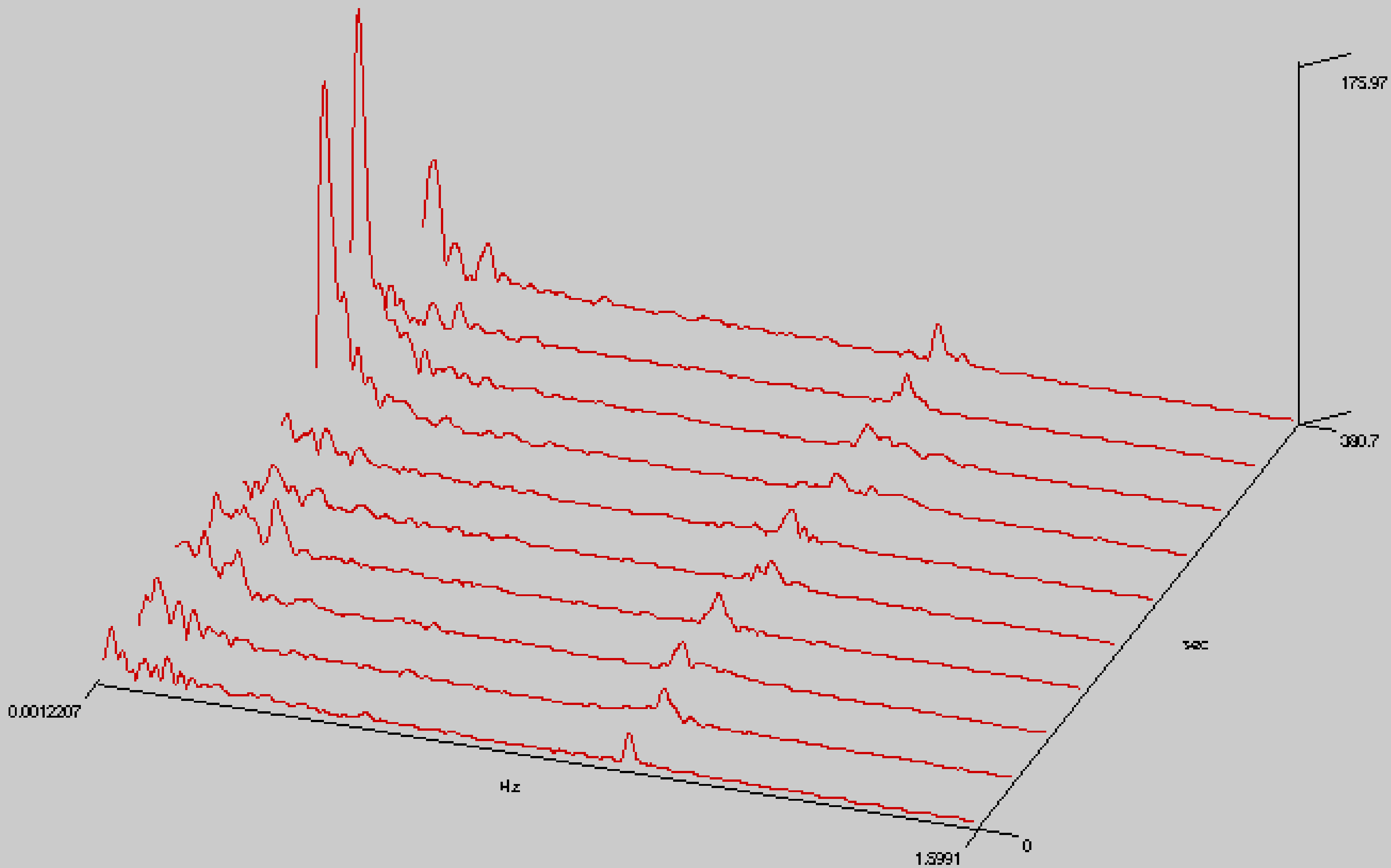
HNM: 20" moor signal at 20 s/sec = 24000 pts on left hand =24000/20=1200 sec
precision=16384, #seg=10 therefore step =1756
precision ~ 16384/20 = 819.2 sec; step ~ 846/20 = 42.3 sec



Precision=number of points per spectrum
Step = S = number of points from start of one spectrum to start of the next

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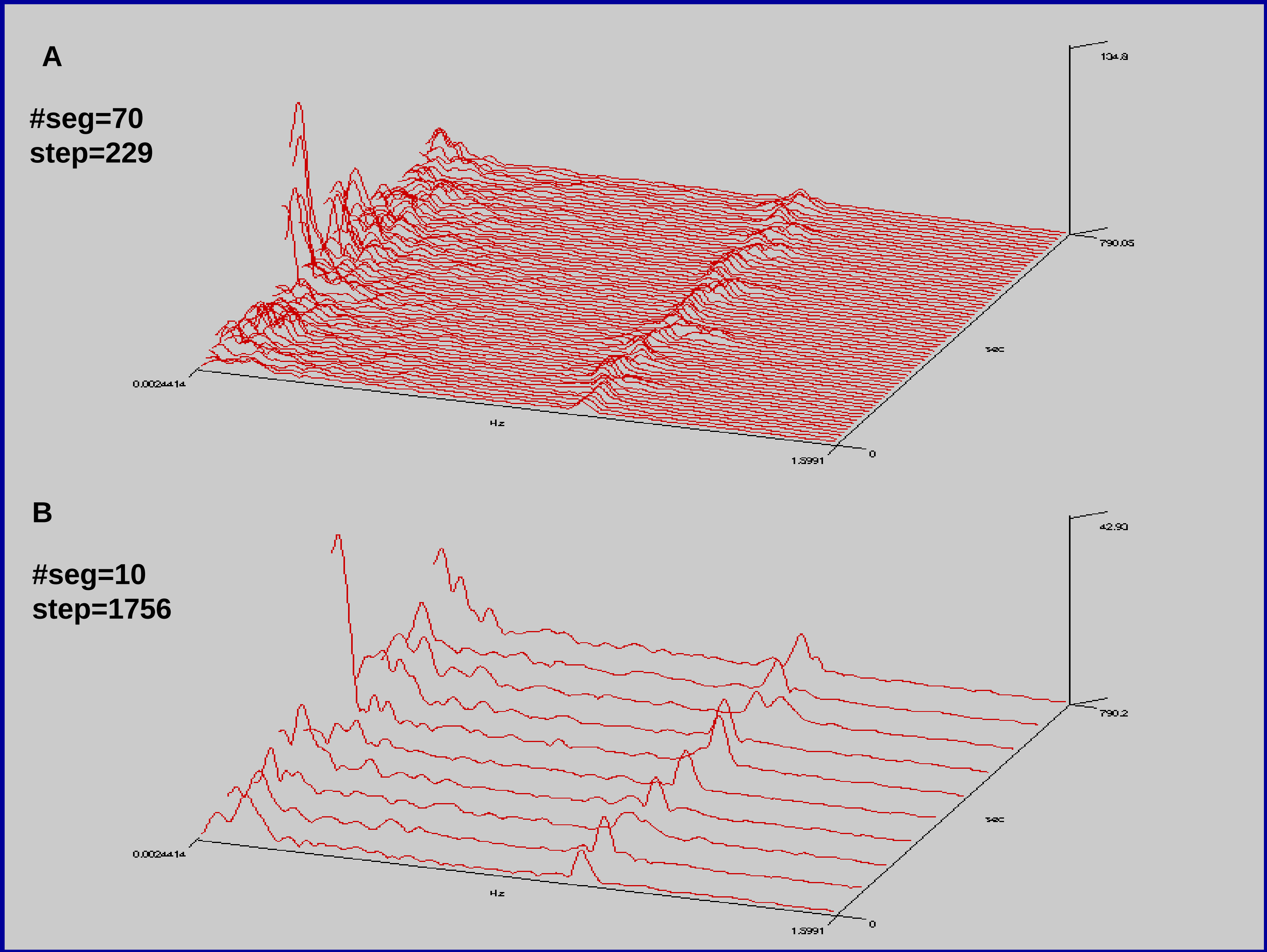
HNM: 20” moor signal at 20 s/s = 24000 pts on LH, both with precision = 8192, Fs = 20



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Variable	Units	Description	Frequency Range
Analysis of Short-term Recordings (5 min)			
5-min total power	ms^2	The variance of NN intervals over the temporal segment	≈≤0.4 Hz
VLF	ms^2	Power in VLF range	≤0.04 Hz
LF	ms^2	Power in LF range	0.04-0.15 Hz
LF norm	nu	LF power in normalized units LF/(total power-VLF)x100	
HF	ms^2	Power in HF range	0.15-0.4 Hz
HF norm	nu	HF power in normalized units HF/(total power-VLF)x100	
LF/HF		Ratio LF [ms^2]/HF[ms^2]	
Analysis of Entire 24 Hours			
Total power	ms^2	Variance of all NN intervals	≈≤0.4 Hz
ULF	ms^2	Power in the ULF range	≤0.003 Hz
VLF	ms^2	Power in the VLF range	0.003-0.04 Hz
LF	ms^2	Power in the LF range	0.04-0.15 Hz
HF	ms^2	Power in the HF range	0.15-0.4 Hz
α		Slope of the linear interpolation of the spectrum in a log-log scale	≈≤0.04 Hz

Variable	Units	Normal Values (mean±SD)
Time Domain Analysis of Nominal 24 hours[181]		
SDNN	ms	141±39
SDANN	ms	127±35
RMSSD	ms	27±12
HRV triangular index		37±15
Spectral Analysis of Stationary Supine 5-min Recording		
Total power	ms^2	3466 ±1018
LF	ms^2	1170±416
HF	ms^2	975±203
LF	nu	54±4
HF	nu	29±3
LF/HF ratio		1.5-2.0