

CS 591 S1 – Computational Audio

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Lecture 16: [Beat Detection and Rhythm Analysis](#)

[Beat Detection](#)

[Tempo Estimation using the FFT](#)

[Higher-level Rhythmic Patterns](#)

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Beat and Tempo



What is the **tactus** or beat?

- Steady pulse that drives music forward and provides the temporal framework of a piece of music
- Sequence of perceived pulses that are equally spaced in time
- The pulse a human taps along when listening to the music

[Parncutt 1994]

[Sethares 2007]

[Large/Palmer 2002]

[Lerdahl/ Jackendoff 1983]

[Fitch/ Rosenfeld 2007]

The term **tempo** then refers to the speed of the pulse.

Beat and Tempo



Strategy

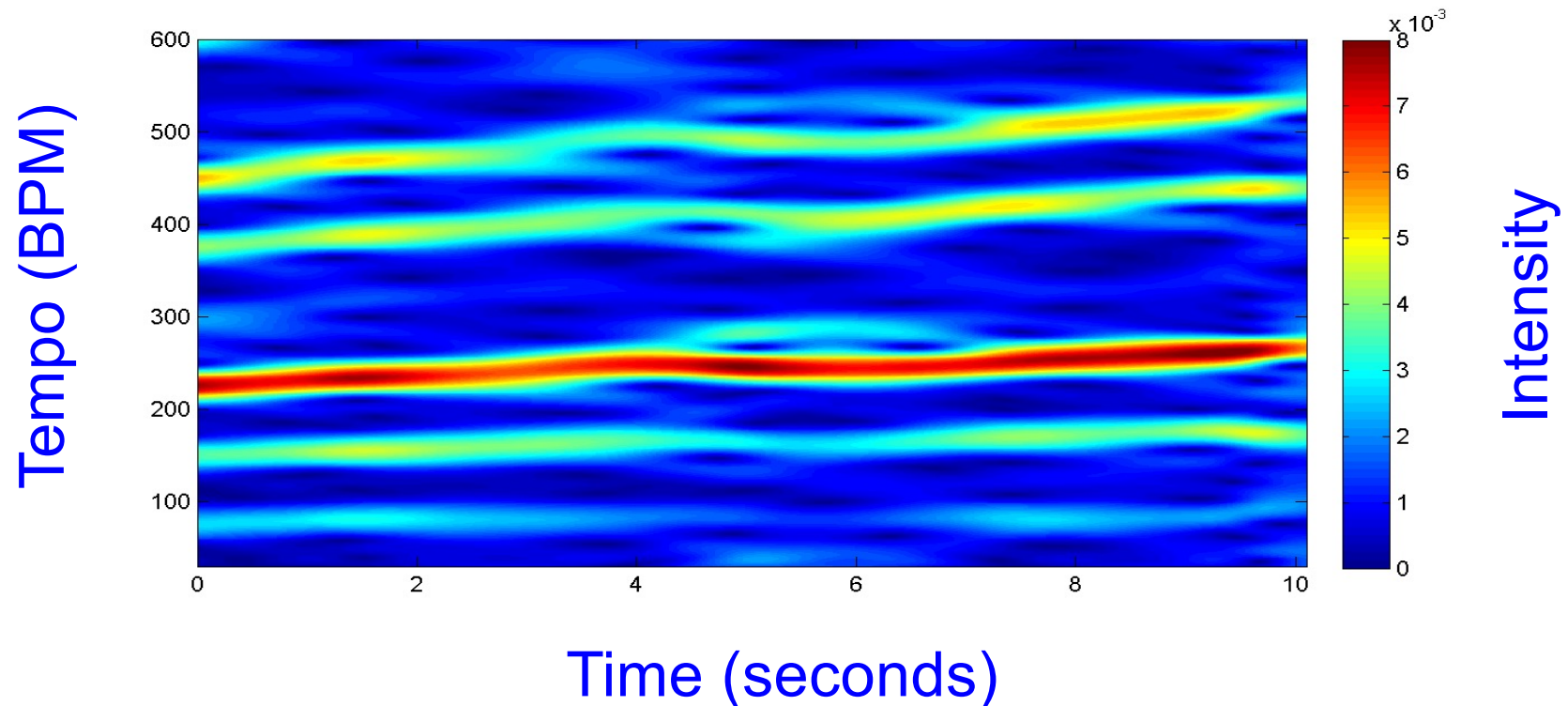
- Analyze the novelty curve with respect to reoccurring or quasi-periodic patterns—as if it were a musical signal and you are trying to find the component pitches (= periodic patterns of the novelty curve)
- Avoid the explicit determination of note onsets (no peak picking)

Methods

- Autocorrelation
- Fourier transform

Tempogram

Definition: A **tempogram** is a time-tempo representation that encodes the local tempo of a music signal over time (= spectrogram of novelty curve!).



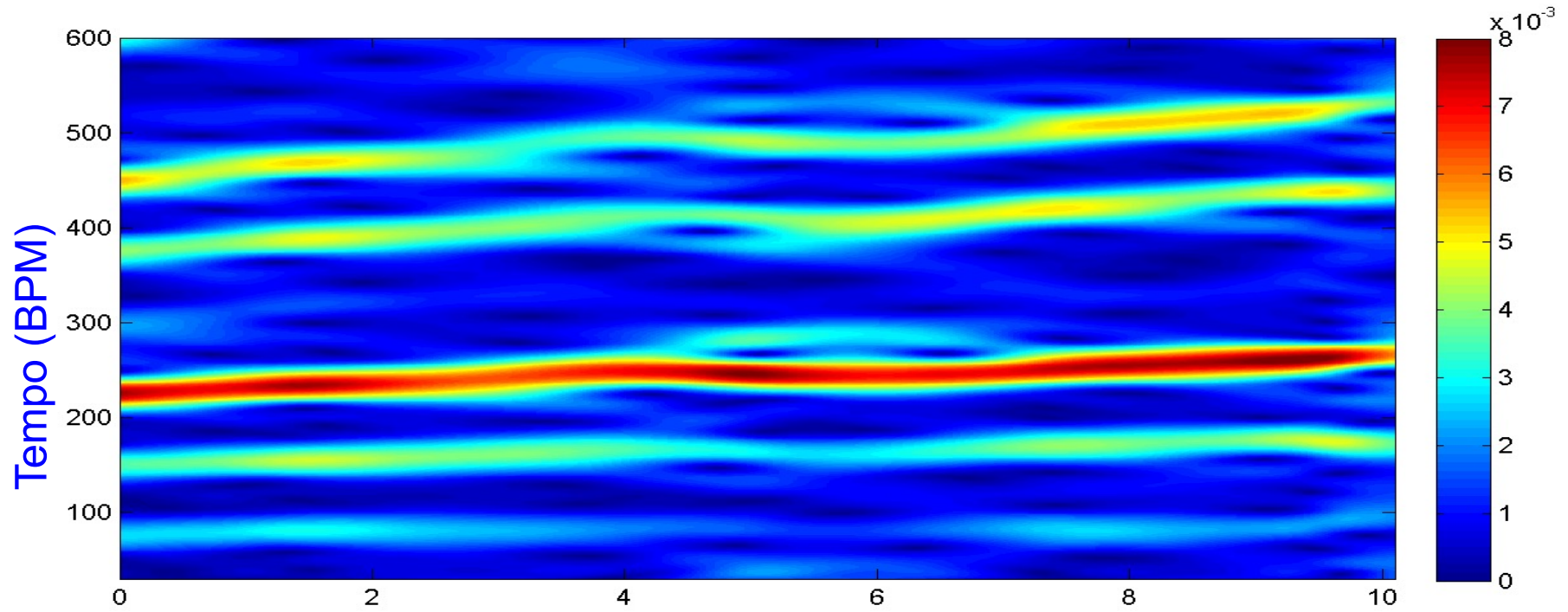
Tempogram (Fourier)

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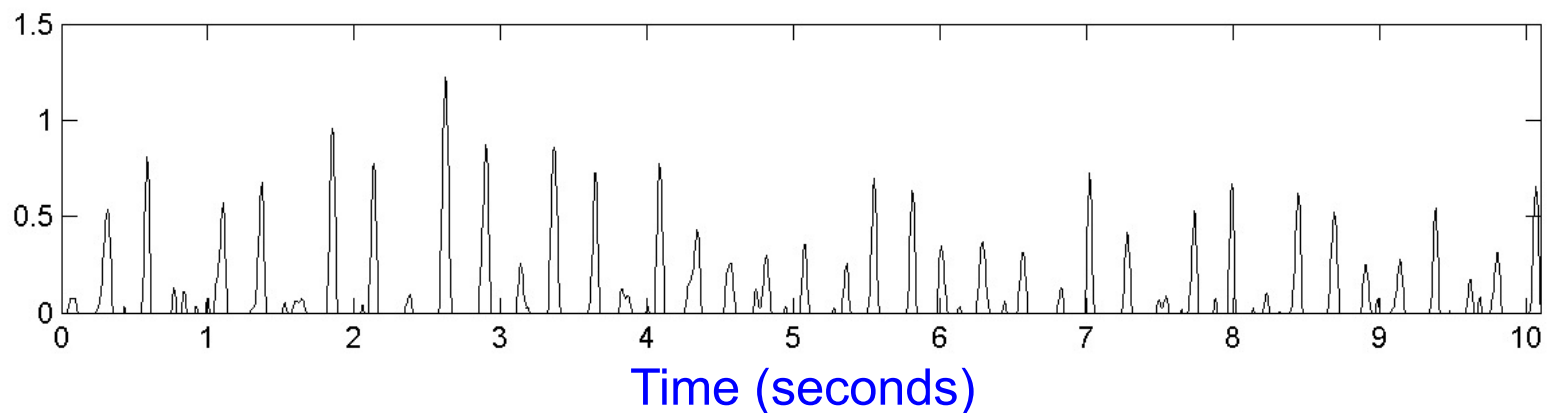
Fourier-based method

- Compute a spectrogram (STFT) of the novelty curve
- Convert frequency axis (given in Hertz) into tempo axis (given in BPM)
- Magnitude spectrogram indicates local tempo

Tempogram (Fourier)

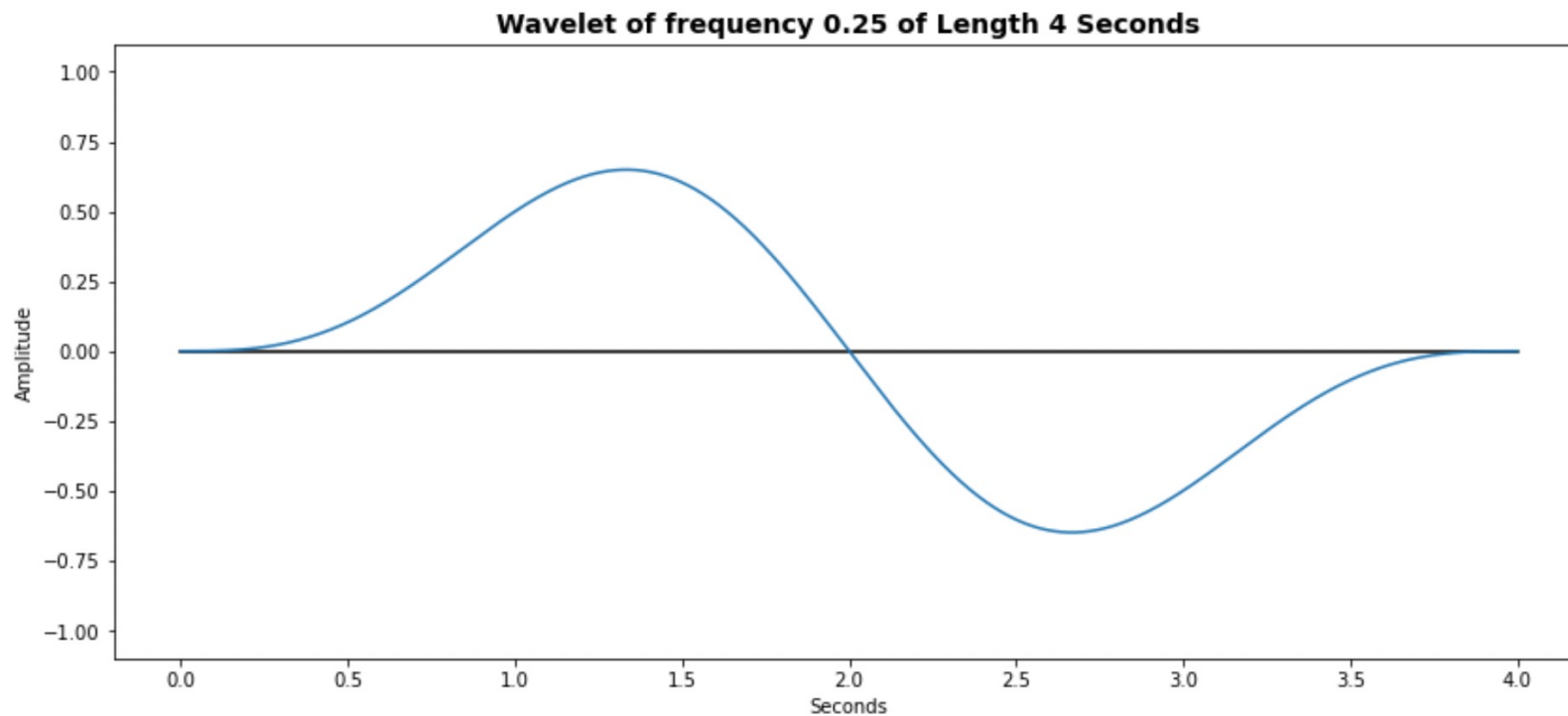


Novelty curve



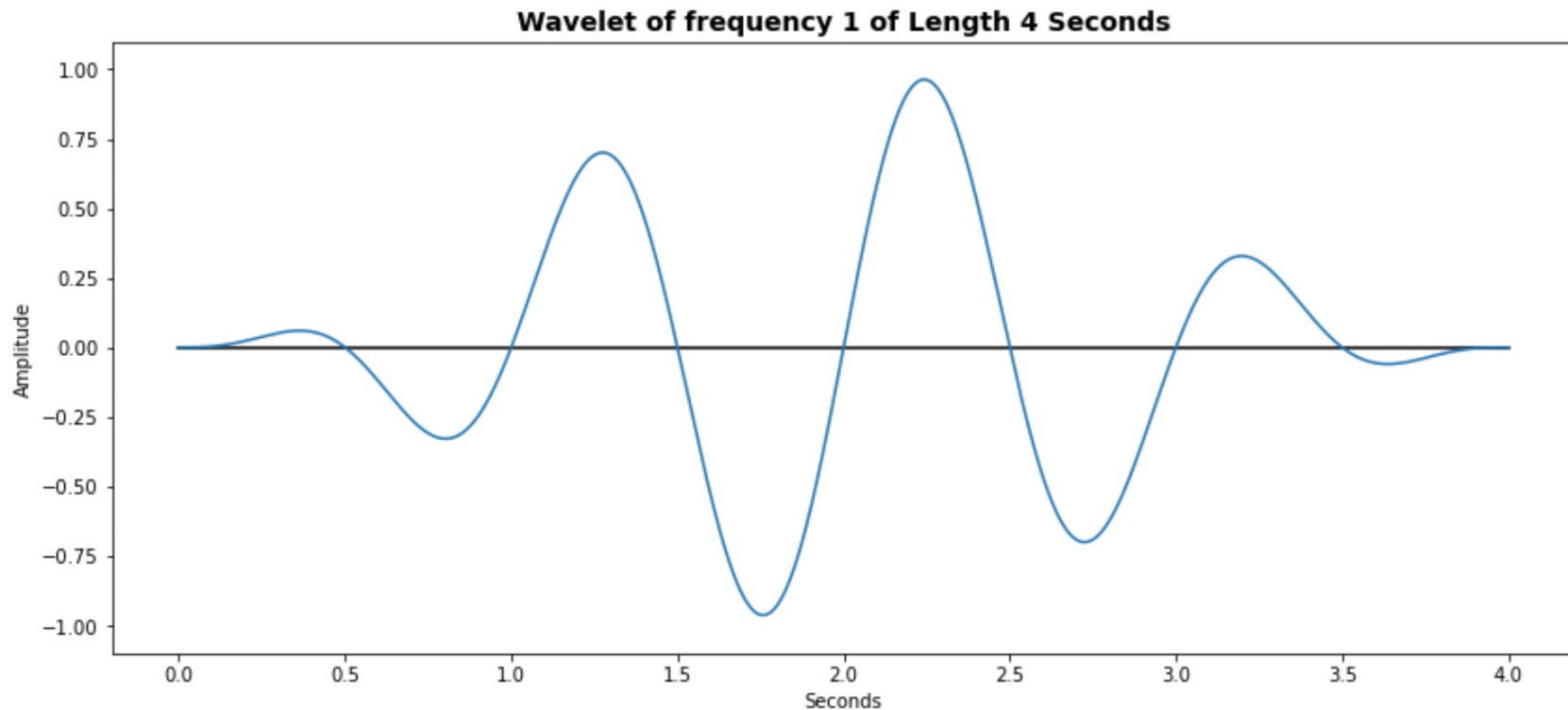
Wavelets

A **wavelet** is a sine wave to which a windowing function has been applied. Typical windowing functions are hann and hamming. The length of the window for beat detection is typically 0.25 – 1.0 seconds, and the skip (hop_length) can be relatively short (0.1 to 0.5 secs).



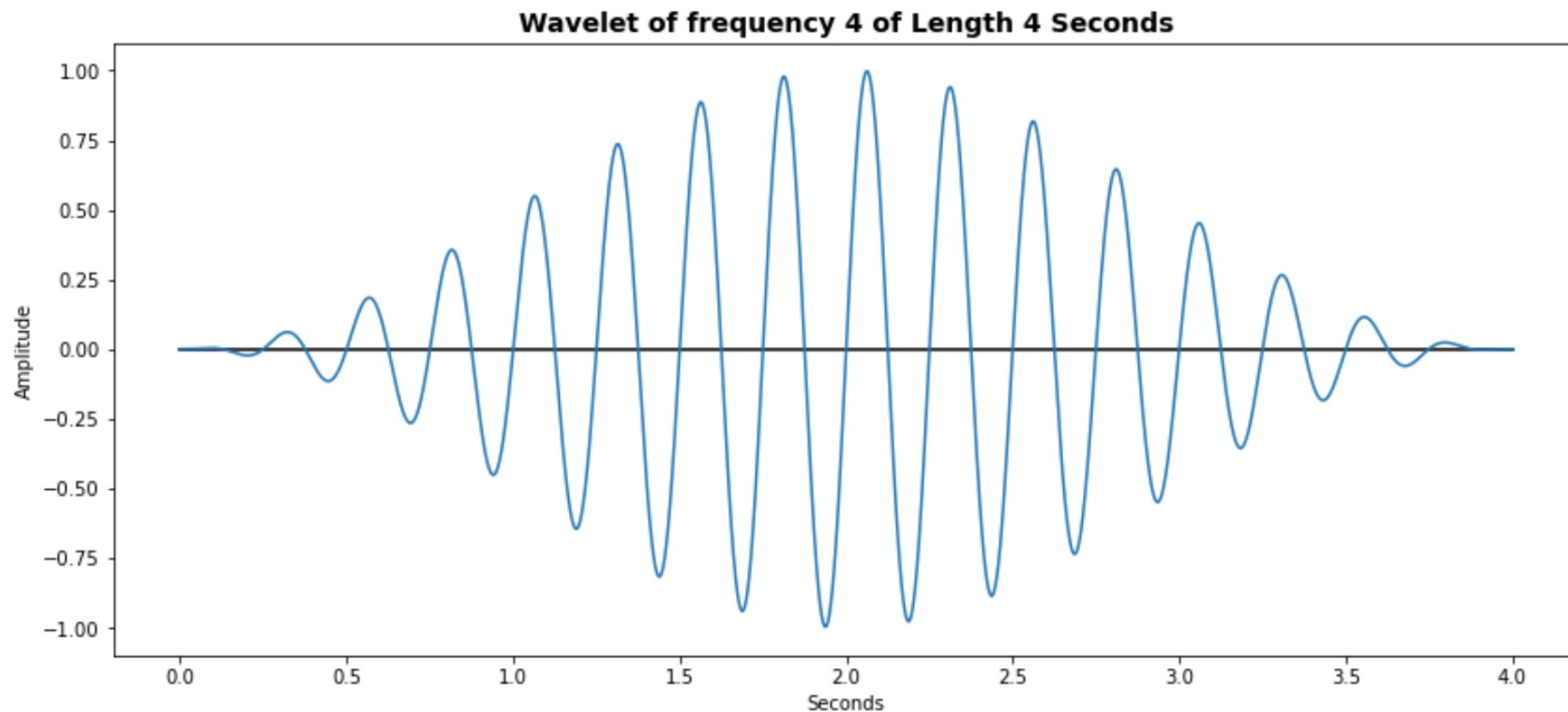
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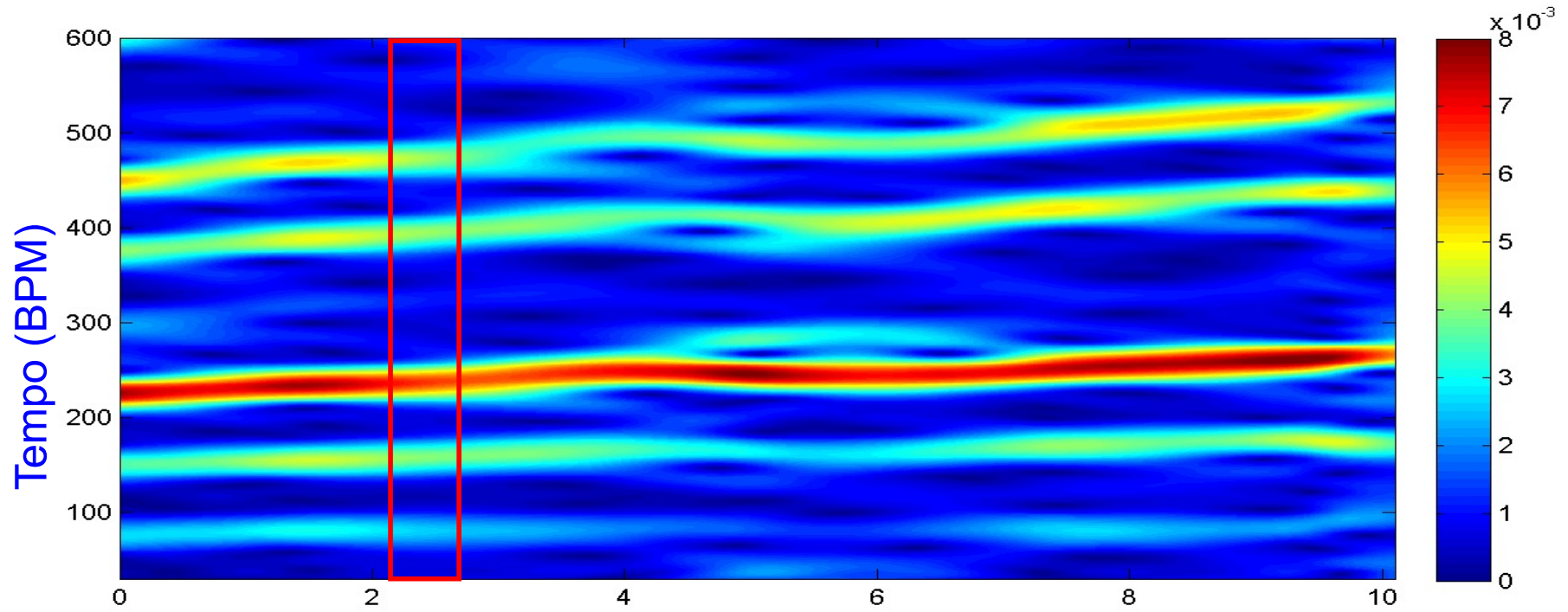


Wavelets

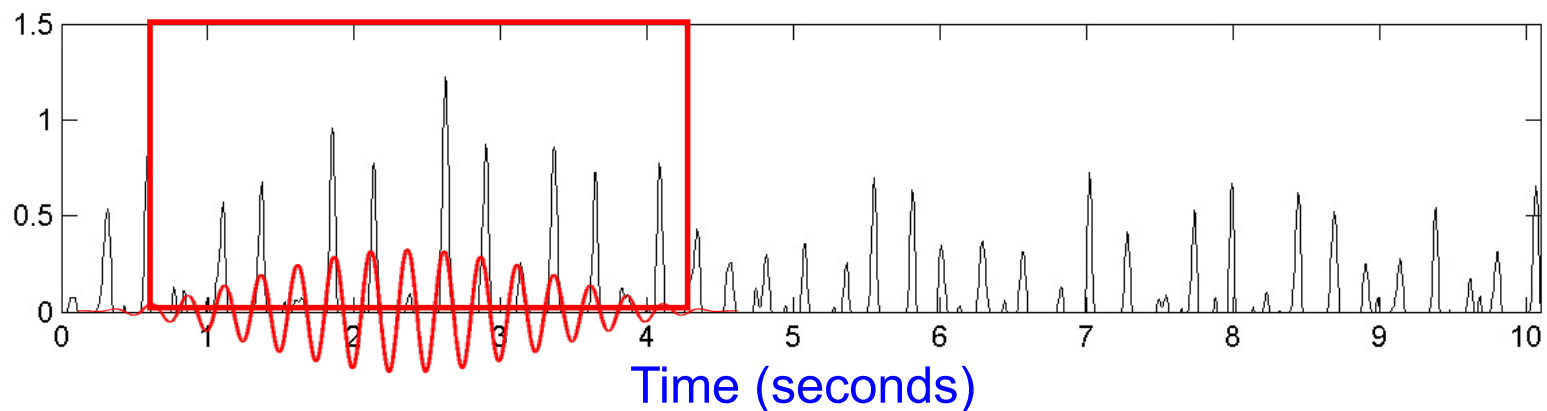
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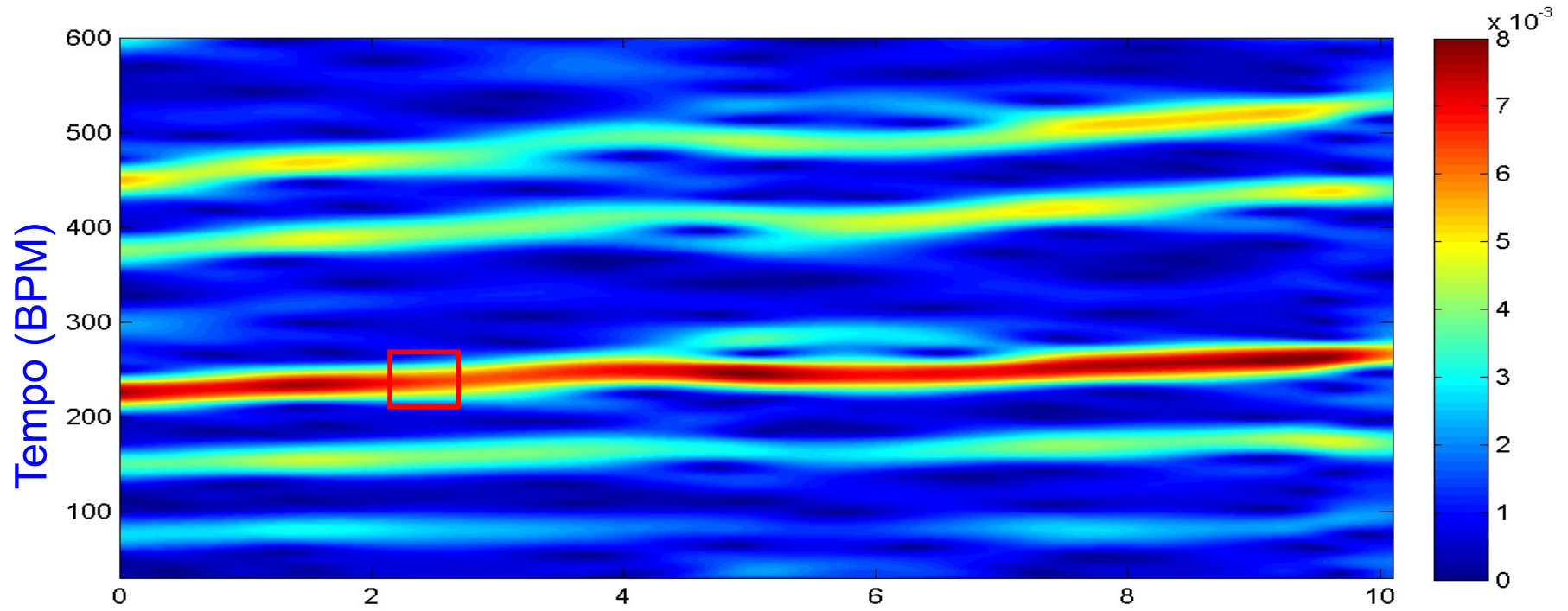
Tempogram (Fourier)



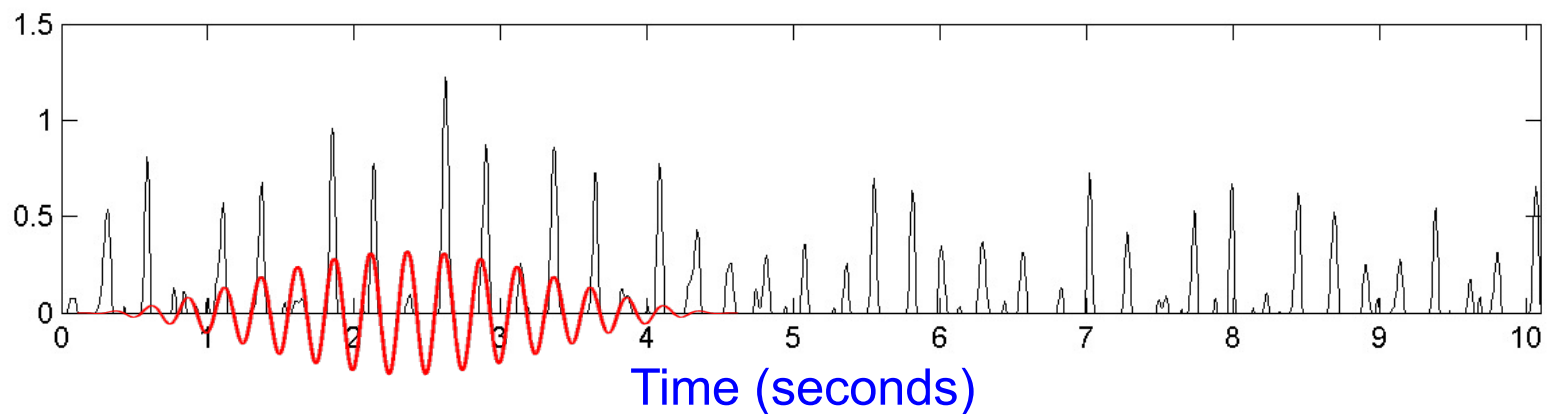
Novelty curve (local window)



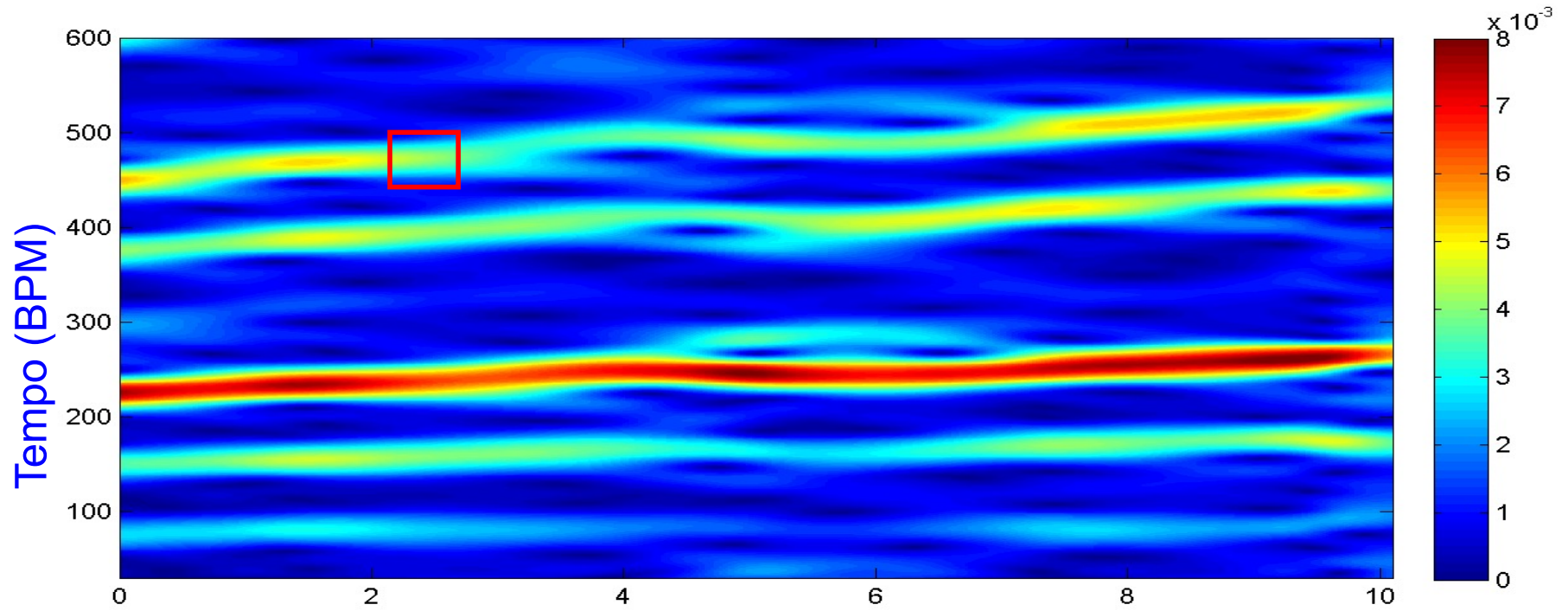
Tempogram (Fourier)



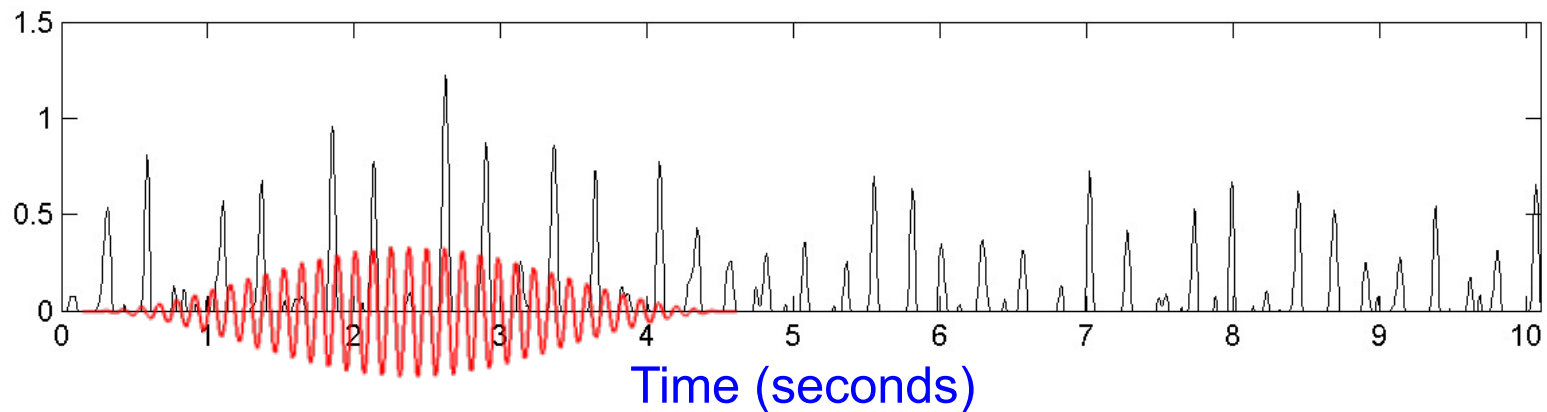
Wavelet-based spectrogram



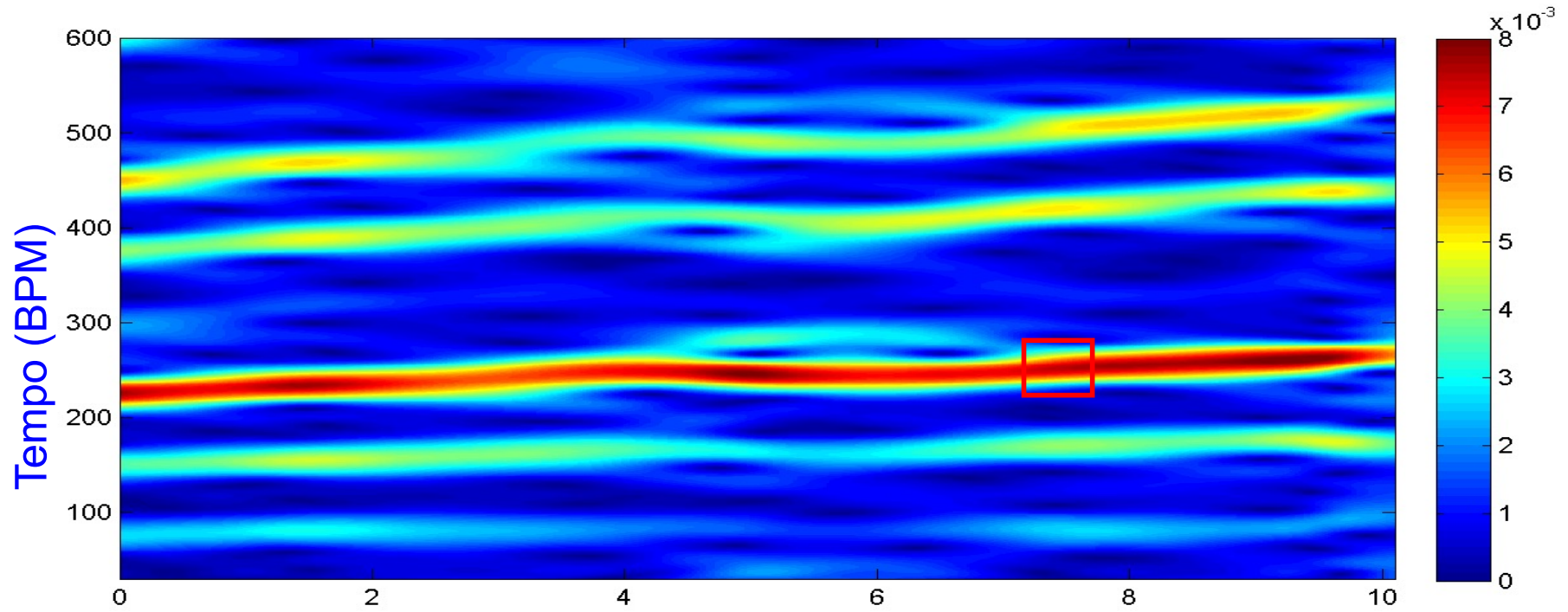
Tempogram (Fourier)



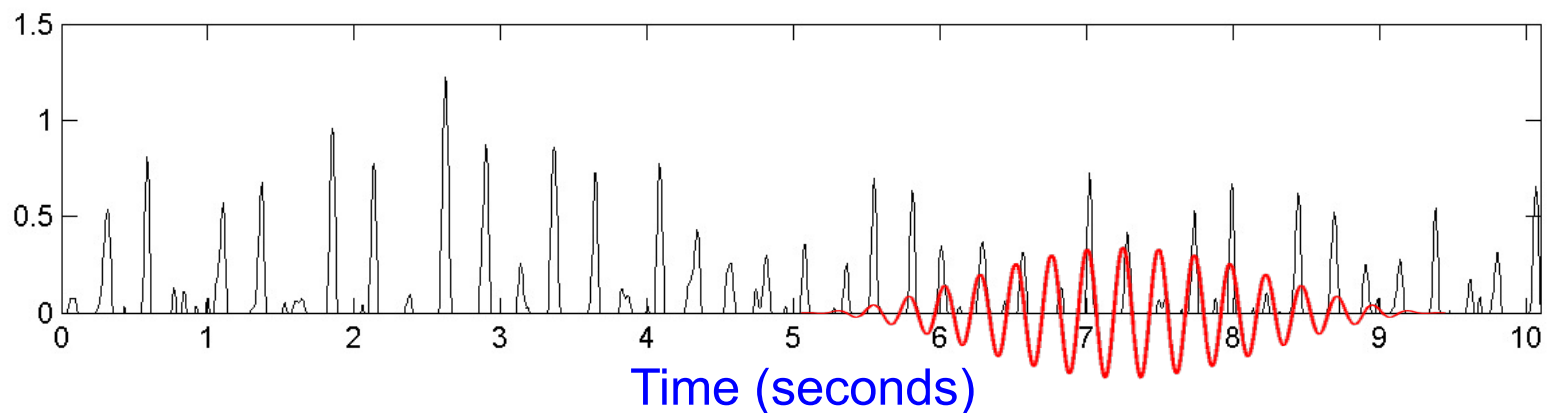
Wavelet-based spectrogram



Tempogram (Fourier)



Wavelet-based spectrogram



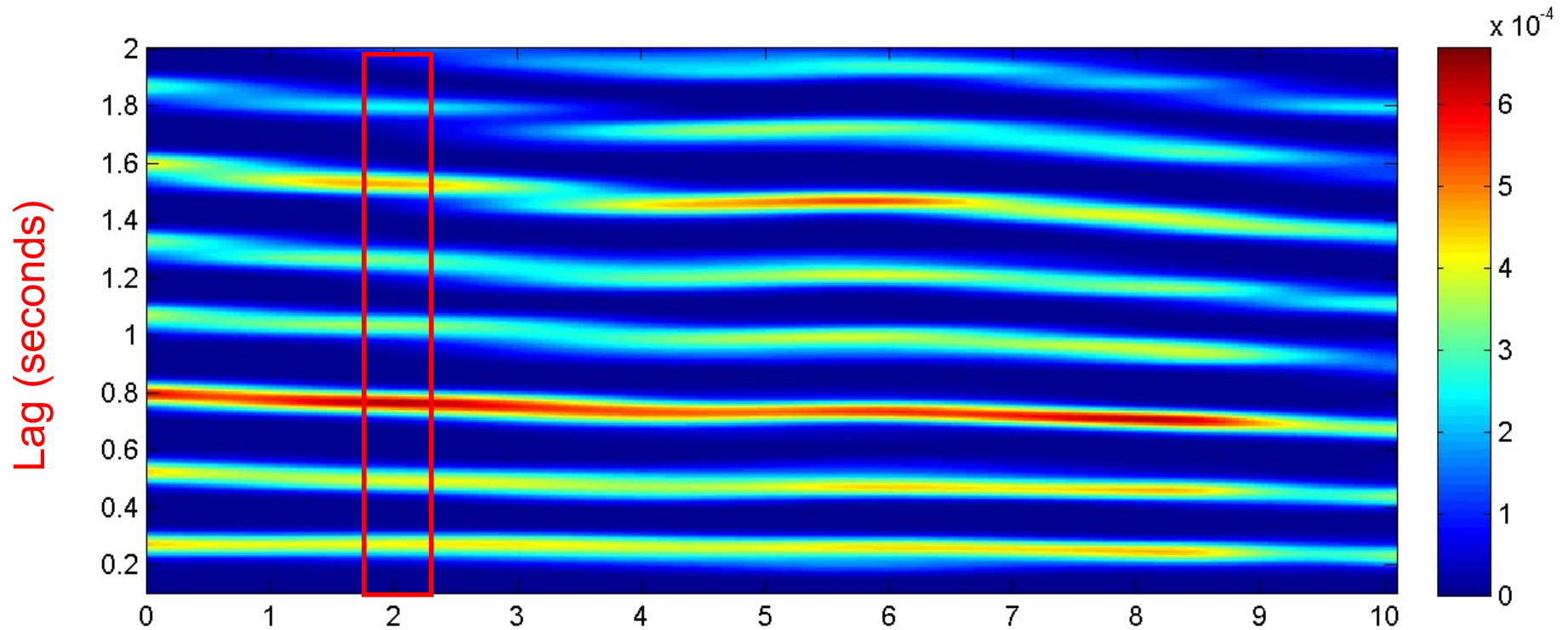
Tempogram (Autocorrelation)

Definition: A **tempogram** is a time-tempo representation that encodes the local tempo of a music signal over time (= spectrograph of novelty curve!).

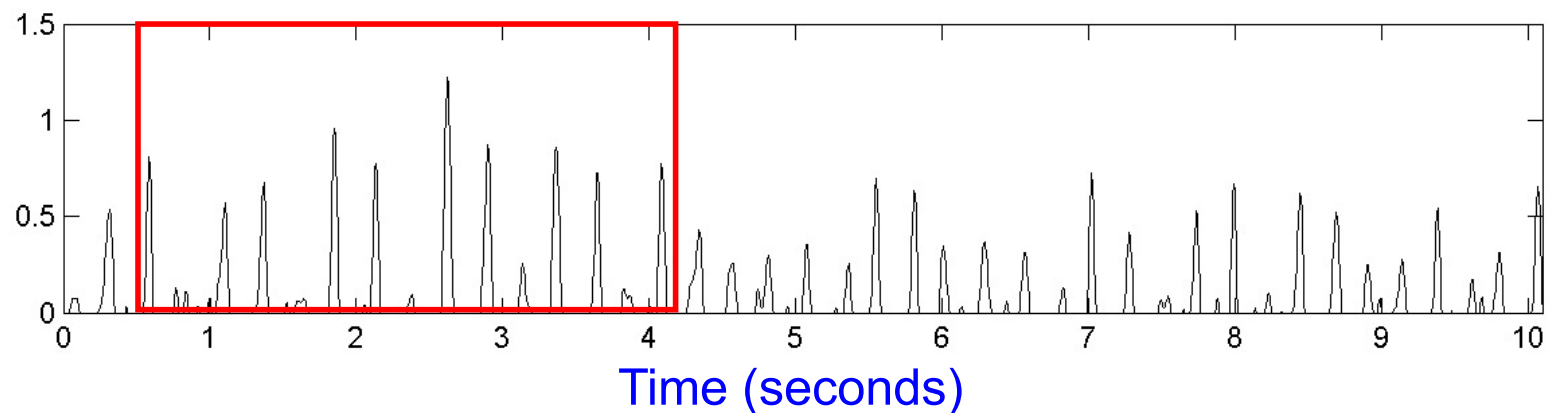
Autocorrelation-based method (cf. pitch determination algorithm).

- Compare novelty curve with time-lagged local sections of itself
- Convert lag-axis (given in seconds) into tempo axis (given in BPM)
- Autocorrelogram indicates local tempo

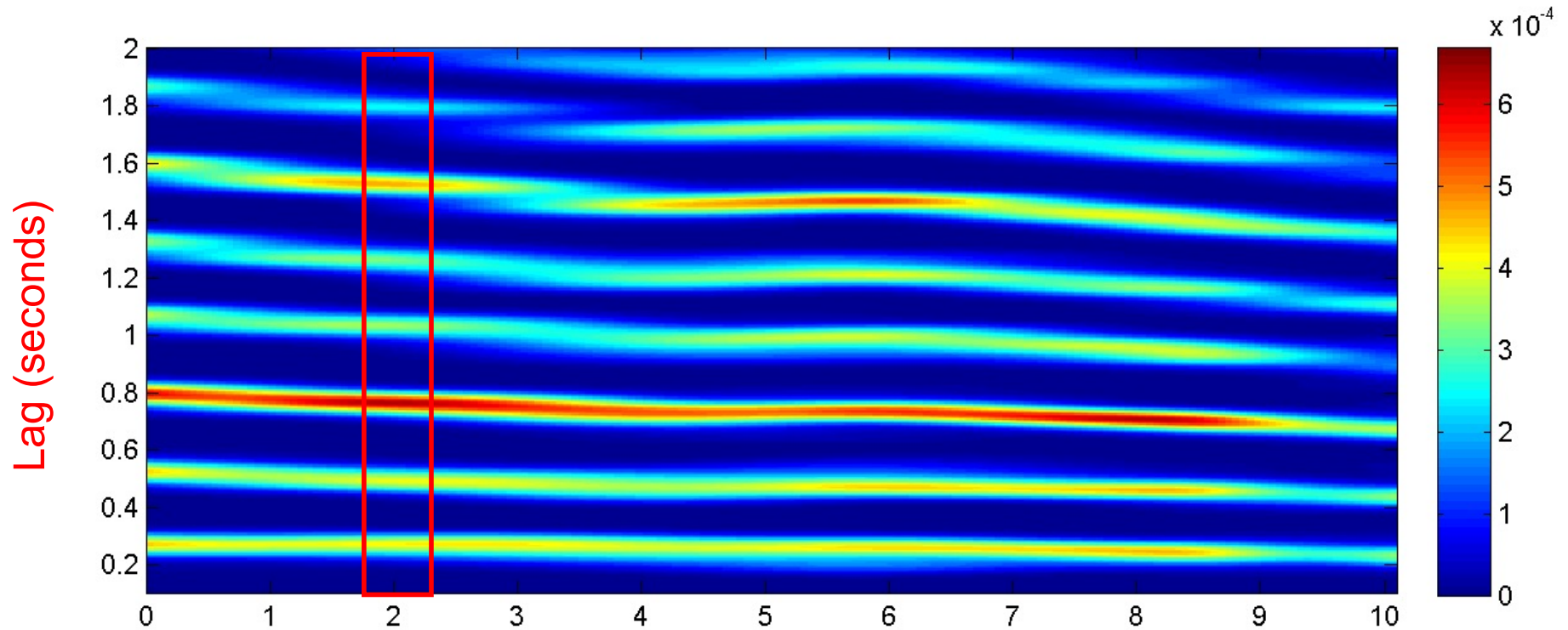
Tempogram (Autocorrelation)



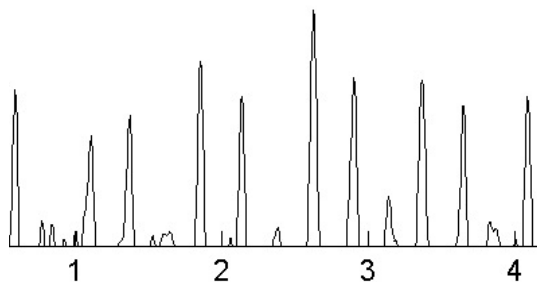
Novelty curve (local window of length 4 secs)



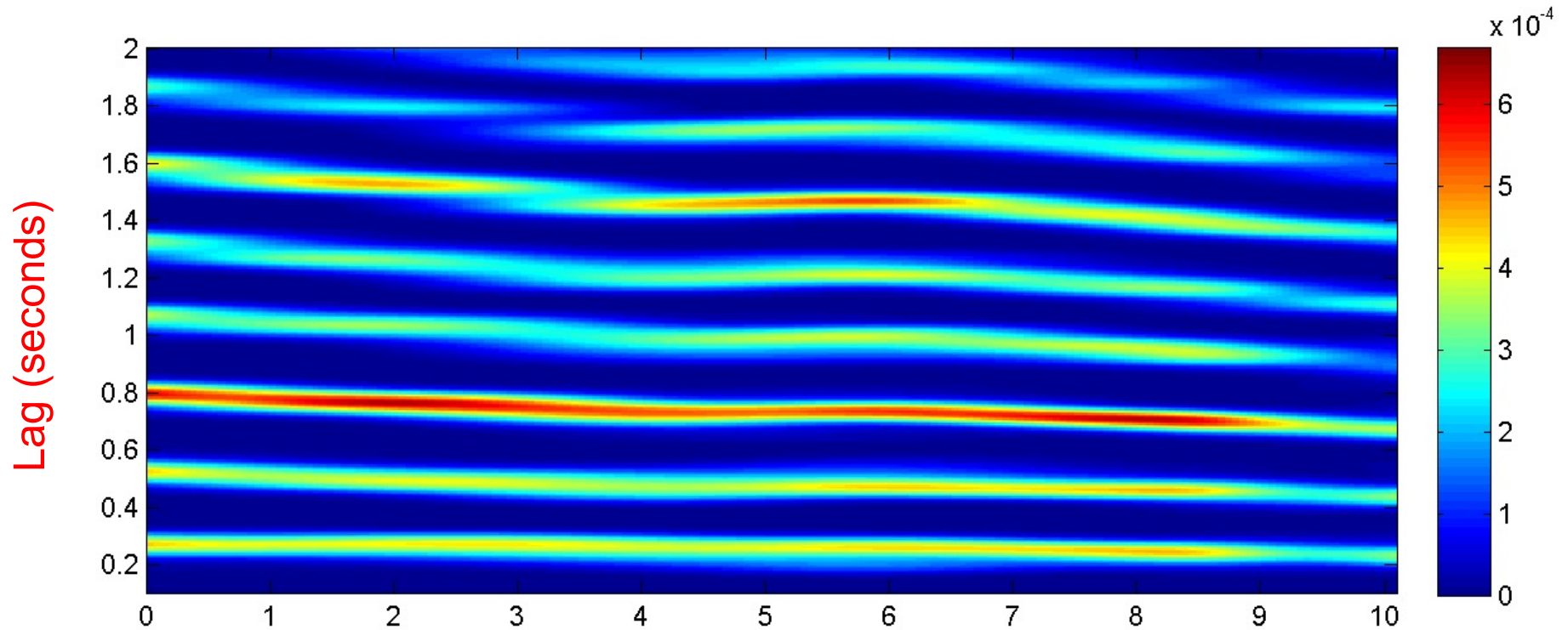
Tempogram (Autocorrelation)



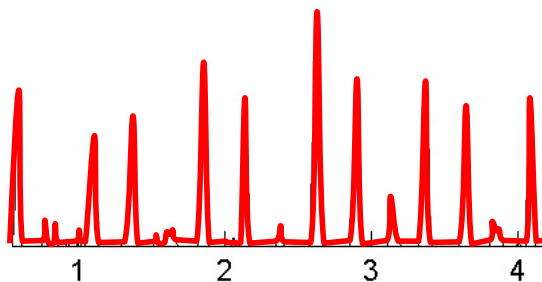
Windowed autocorrelation



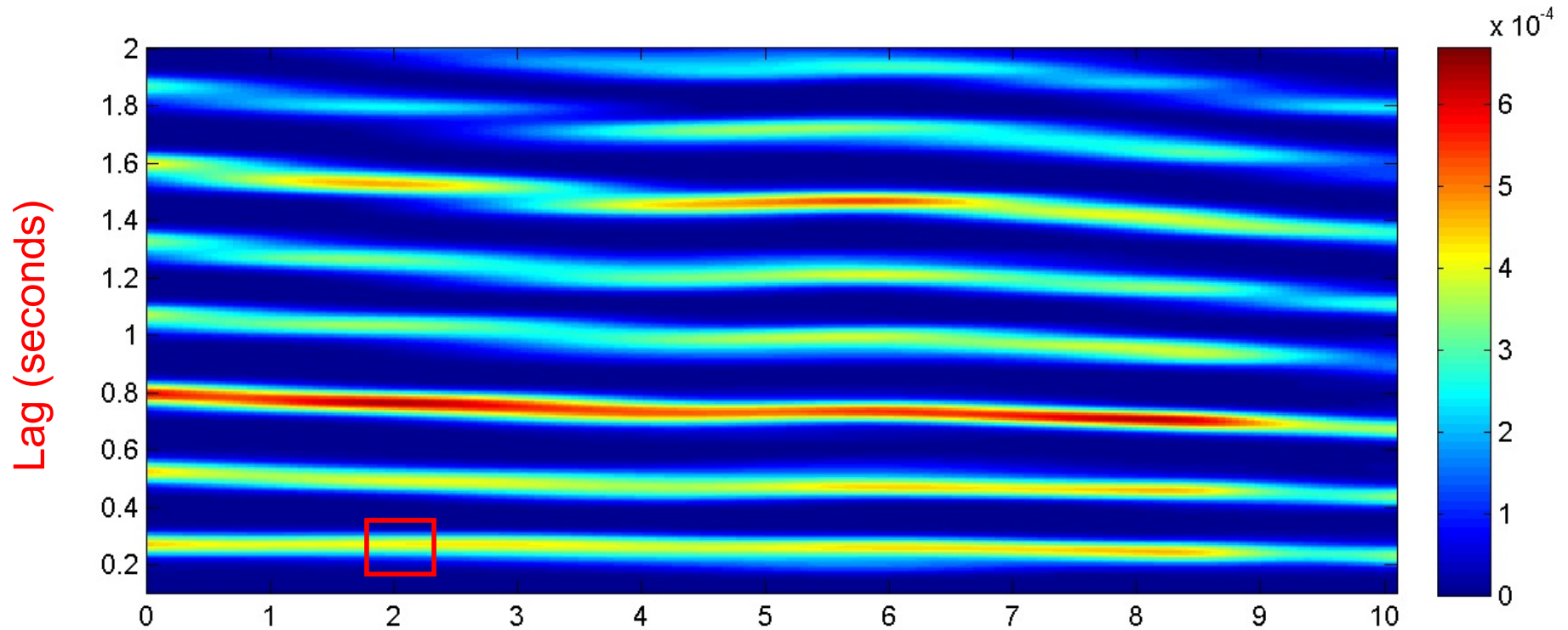
Tempogram (Autocorrelation)



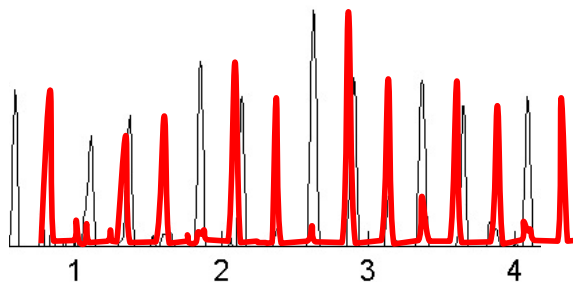
Lag = 0 (seconds)



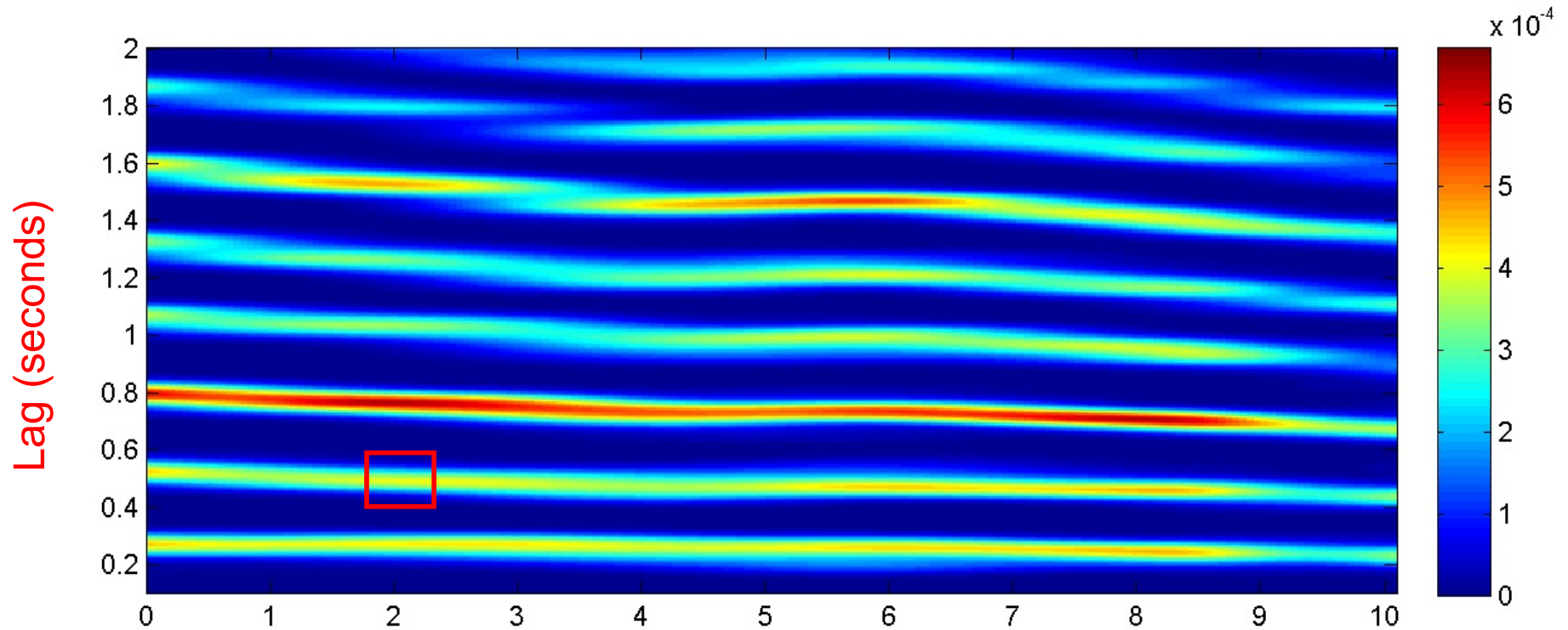
Tempogram (Autocorrelation)



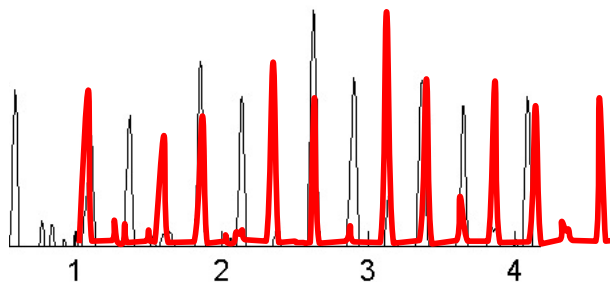
Lag = 0.26 (seconds)



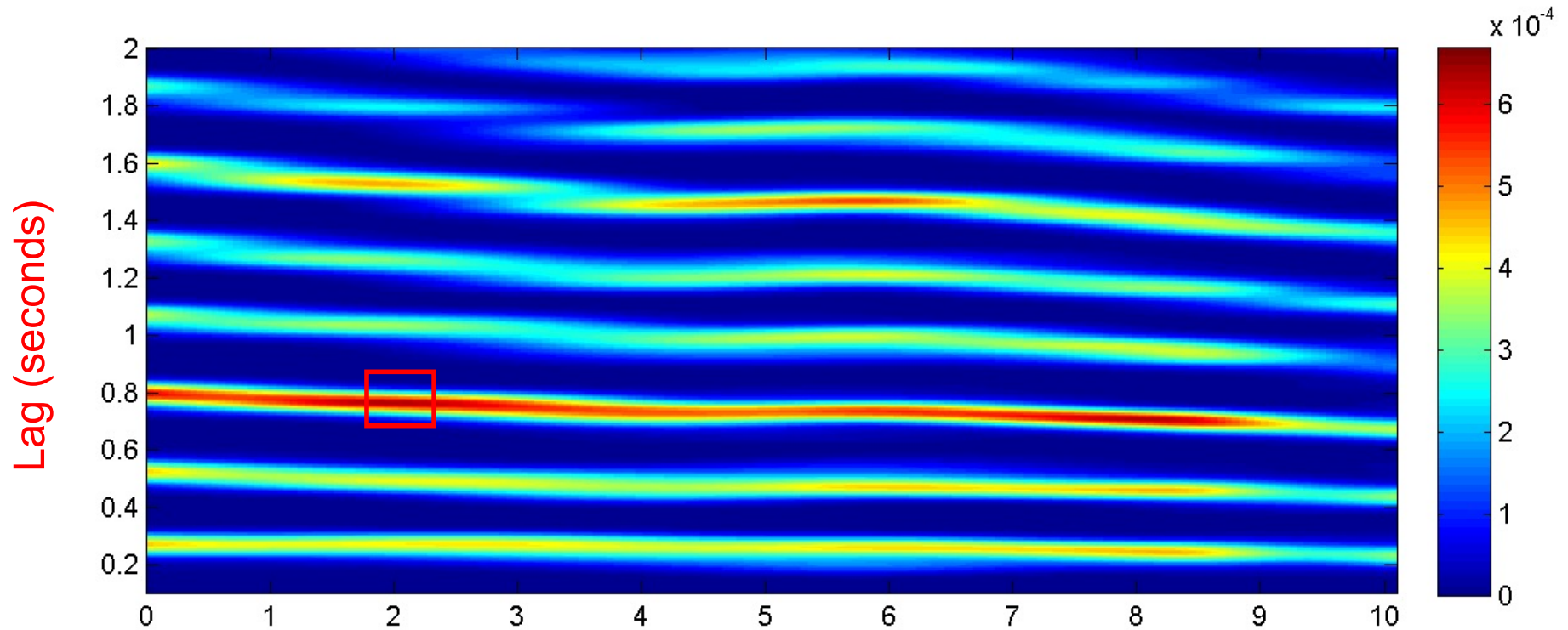
Tempogram (Autocorrelation)



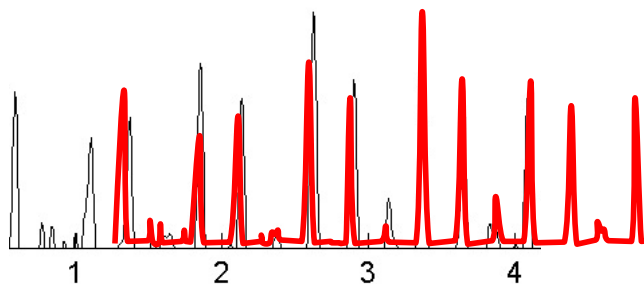
Lag = 0.52 (seconds)



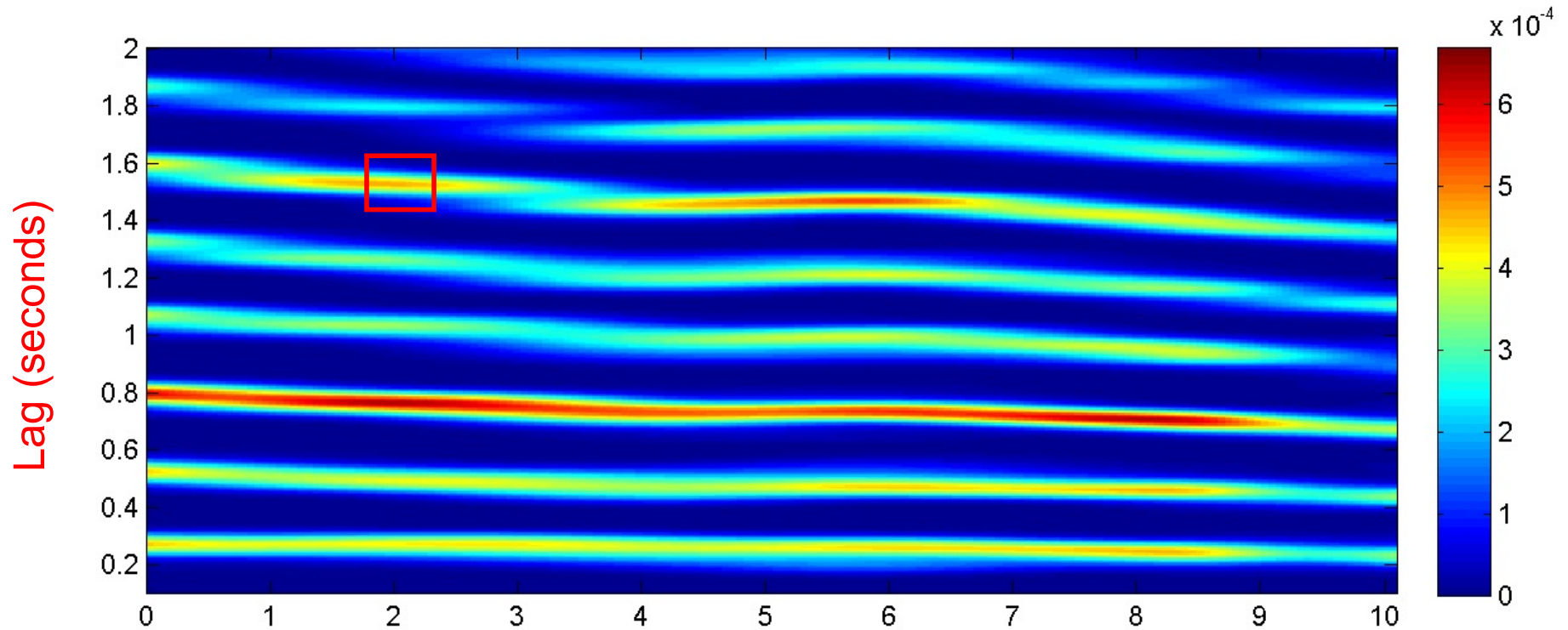
Tempogram (Autocorrelation)



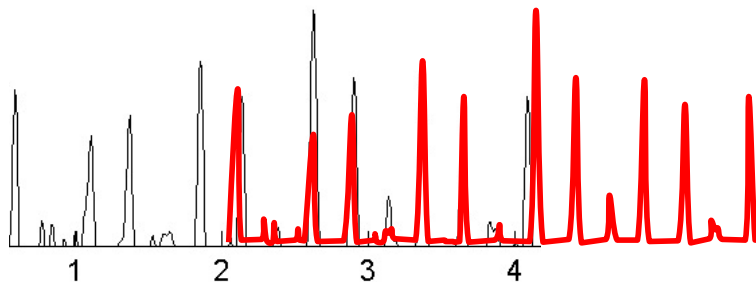
Lag = 0.78 (seconds)



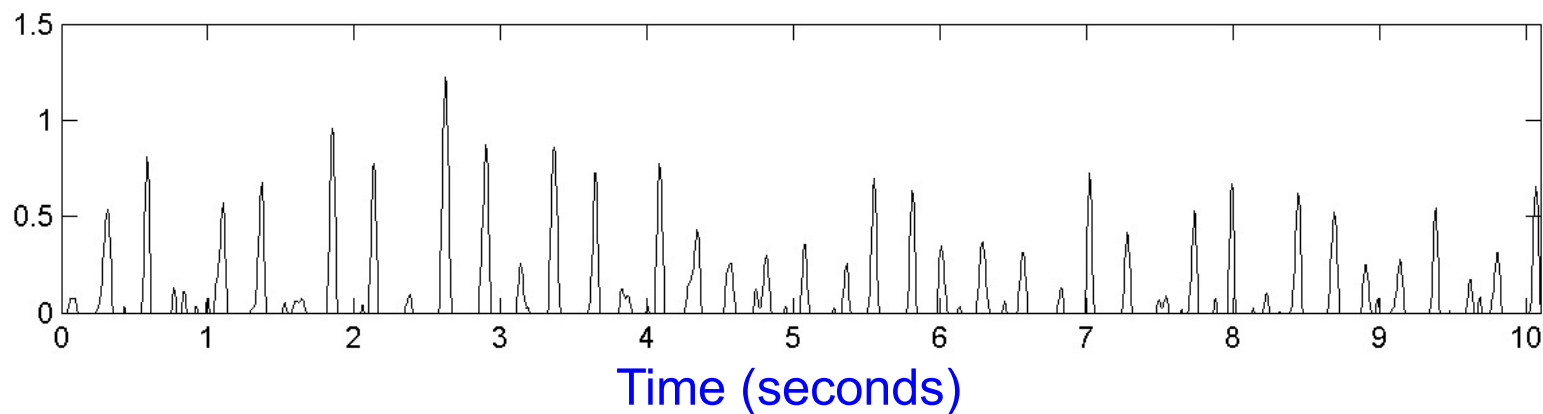
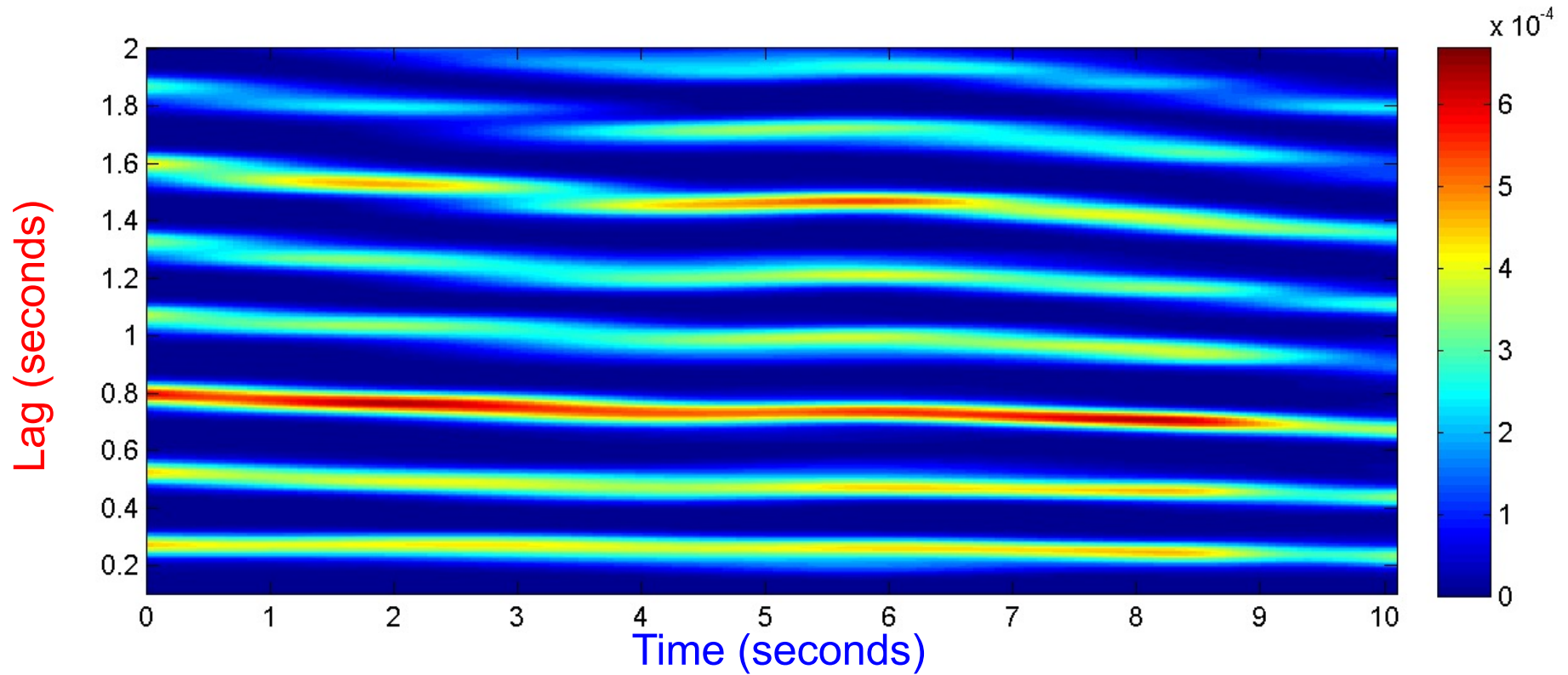
Tempogram (Autocorrelation)



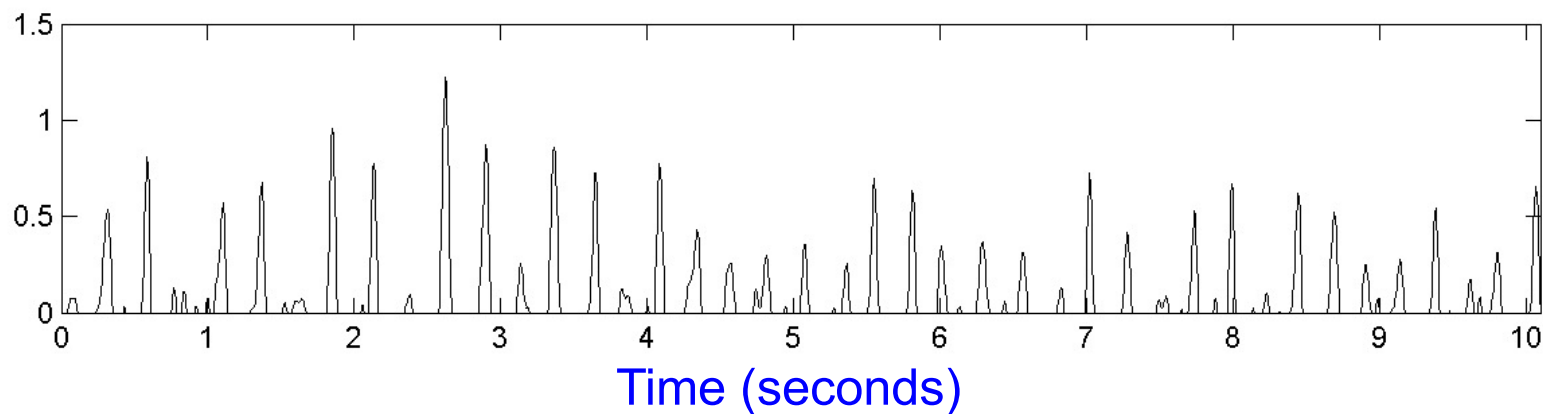
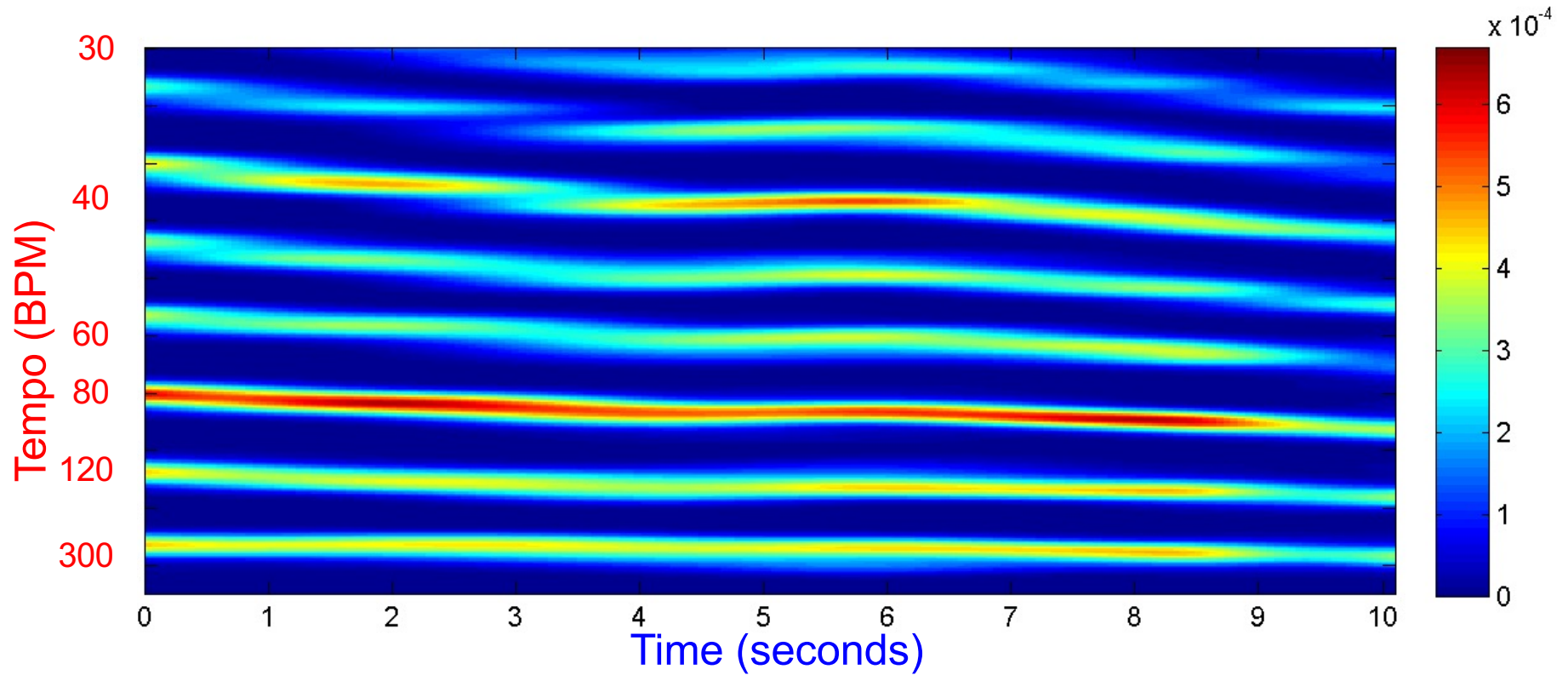
Lag = 1.56 (seconds)



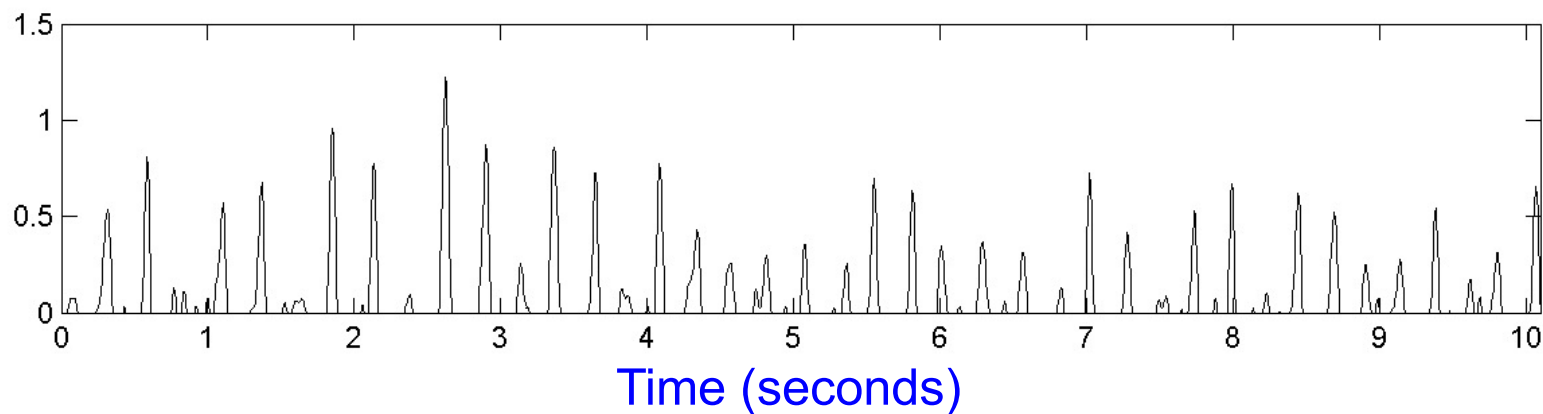
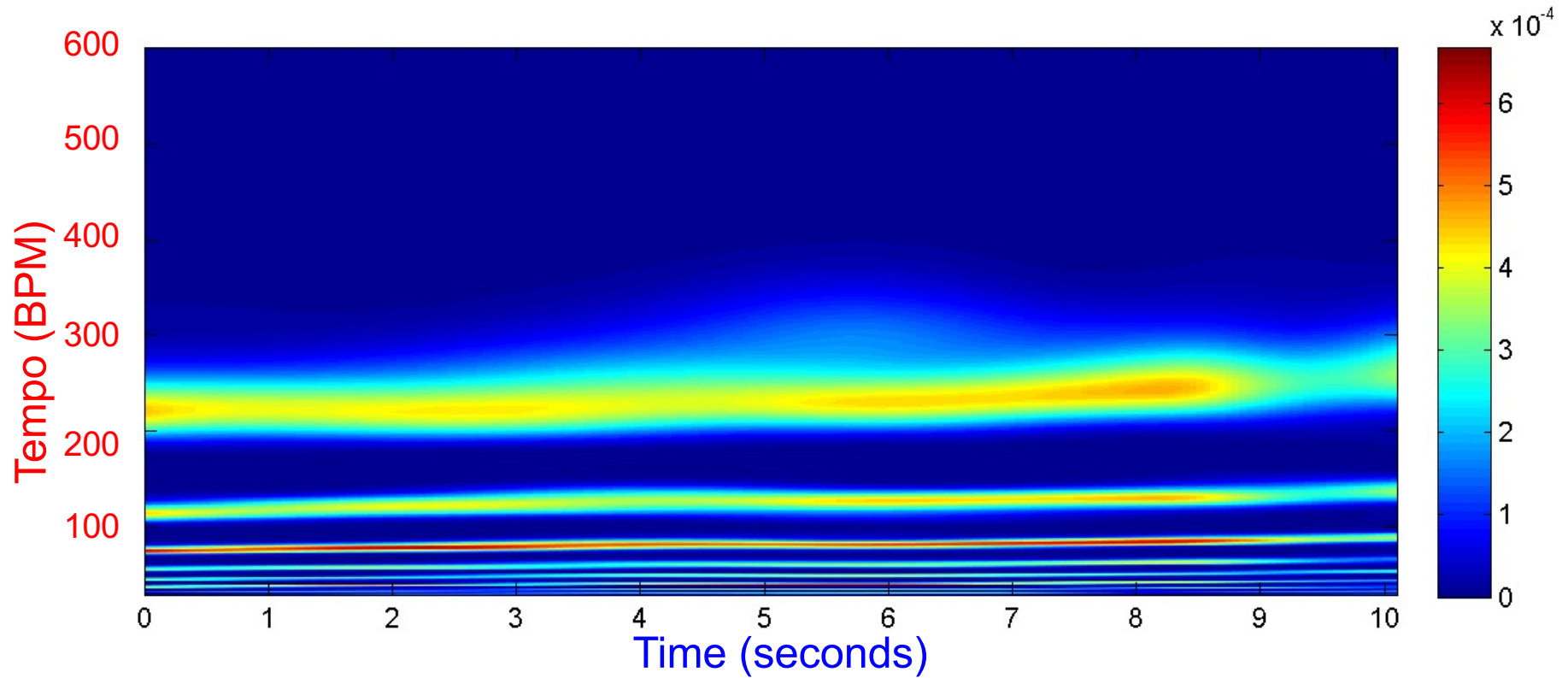
Tempogram (Autocorrelation)



Tempogram (Autocorrelation)

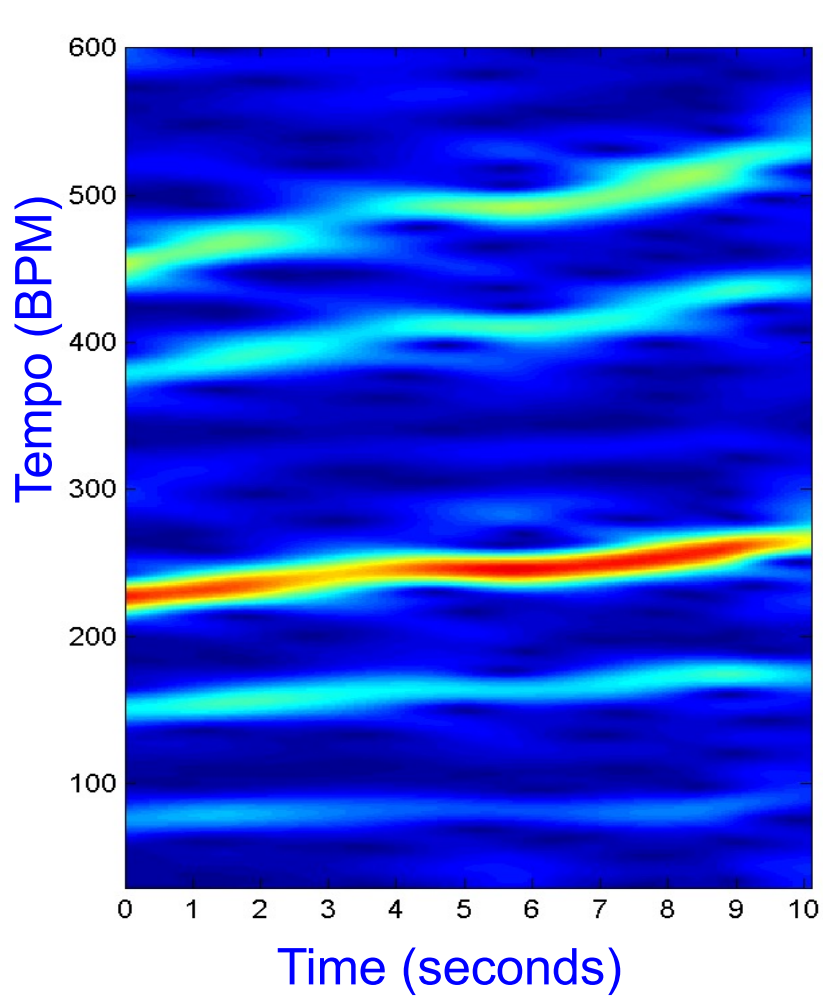


Tempogram (Autocorrelation)

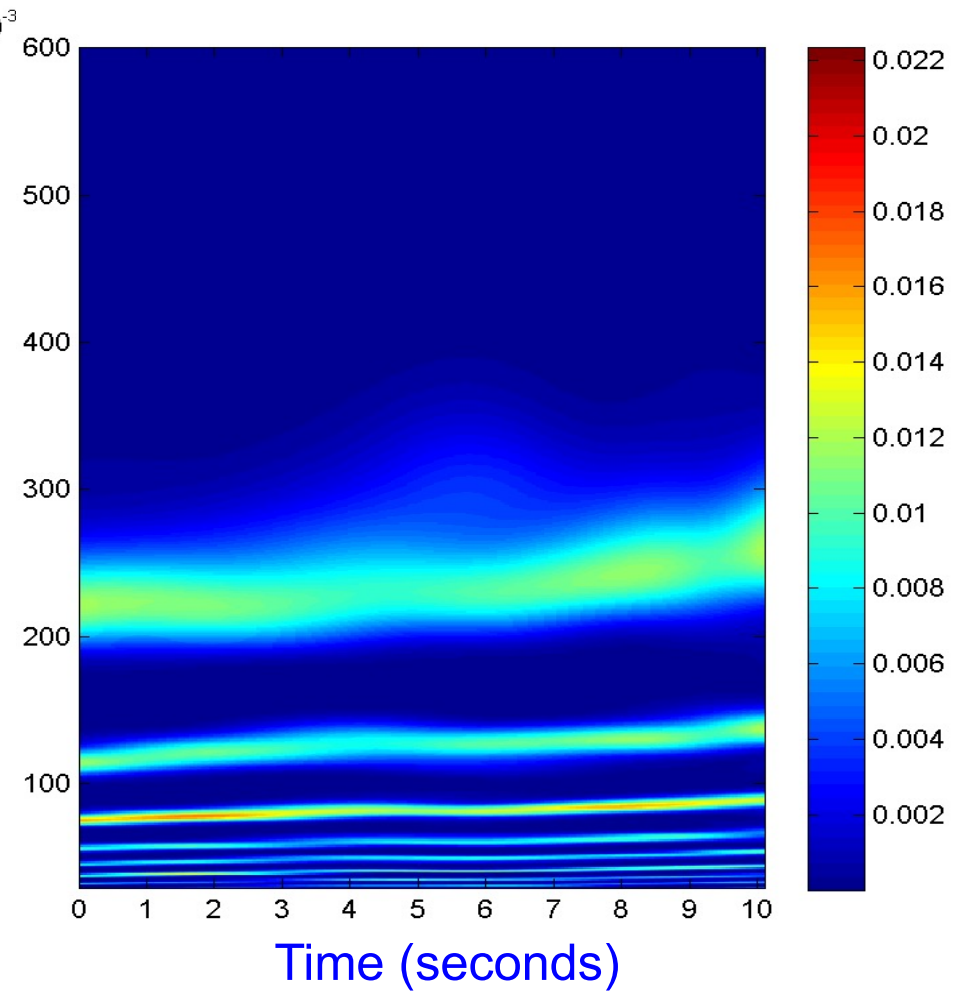


Tempogram

Fourier

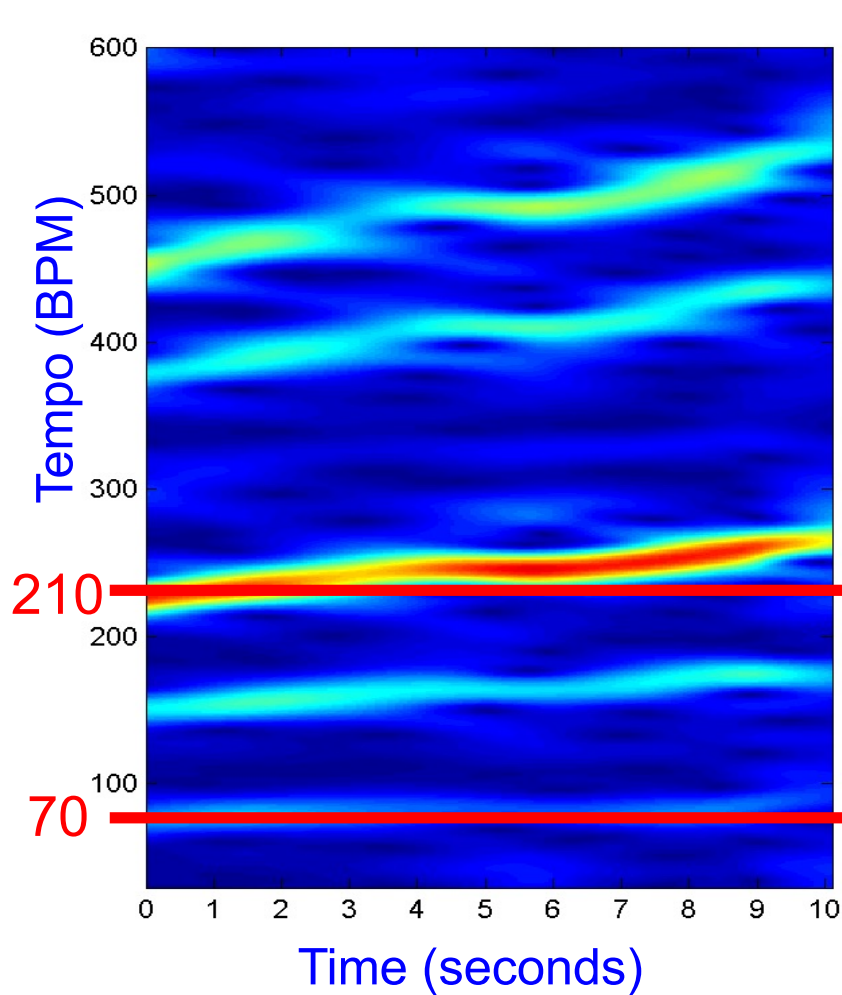


Autocorrelation

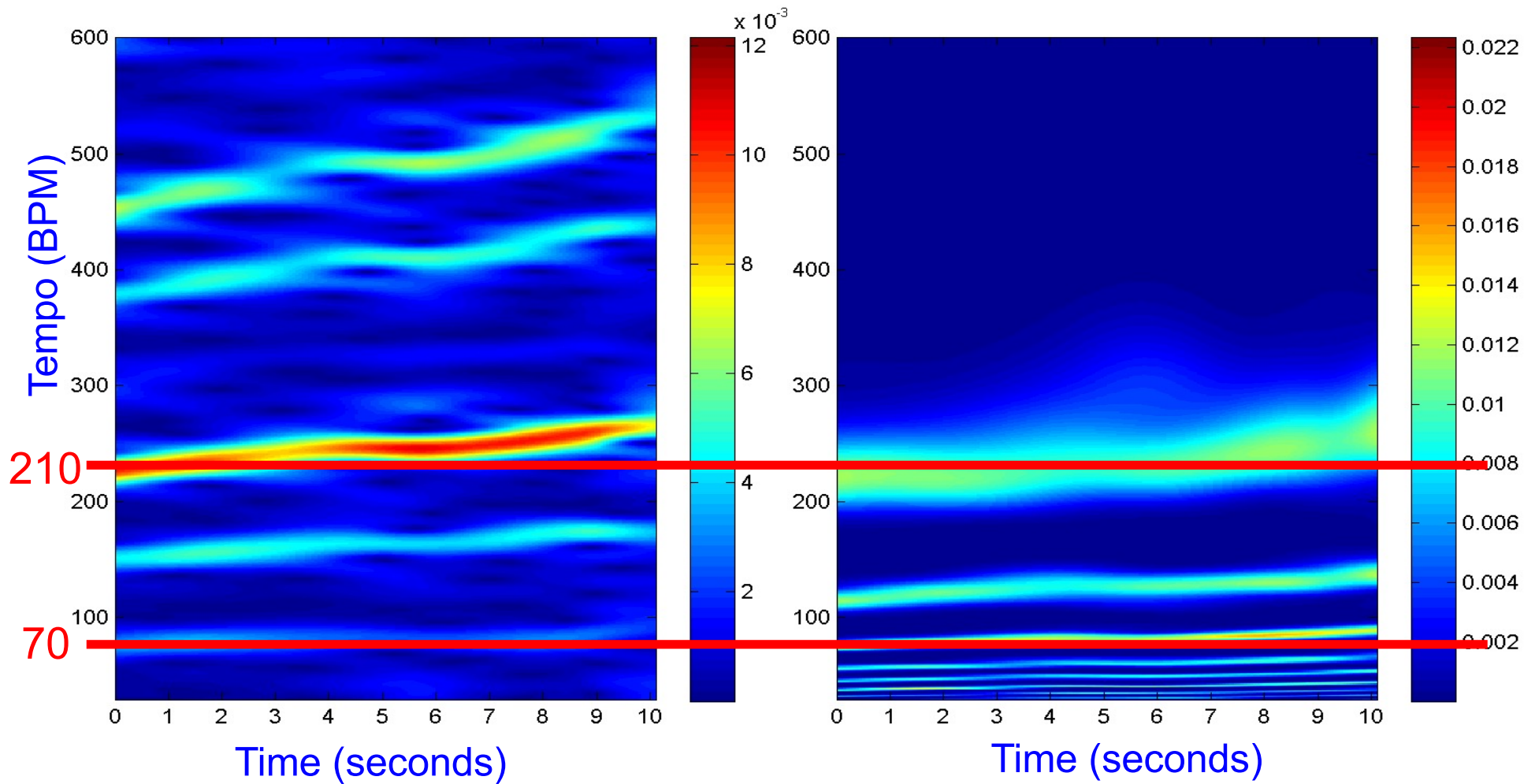


Tempogram

Fourier



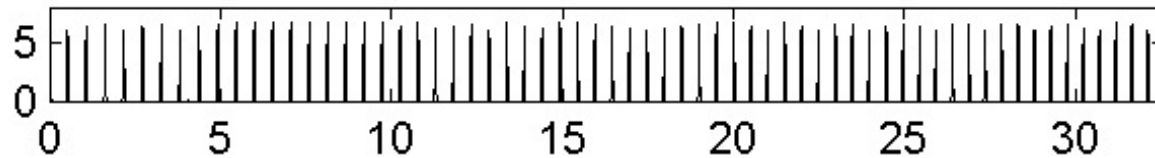
Autocorrelation



Tempo@Tatum = 210 BPM

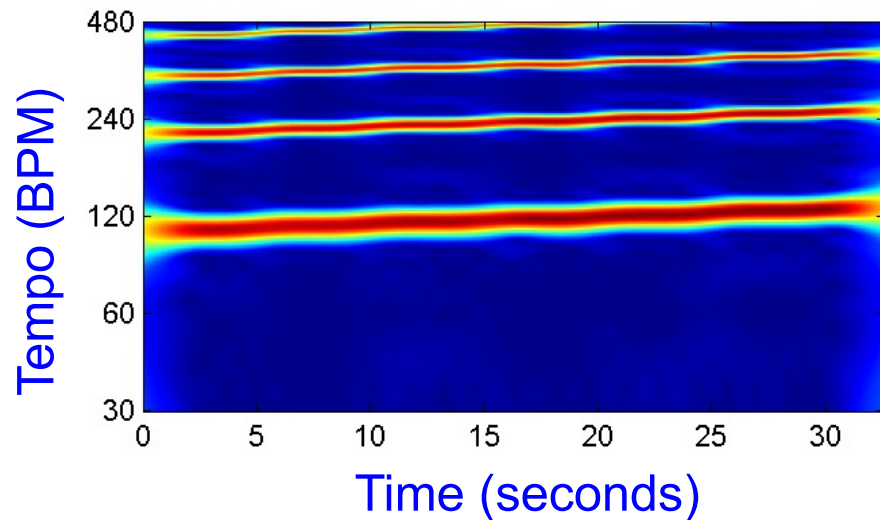
Tempo@Measure = 70 BPM

Tempogram



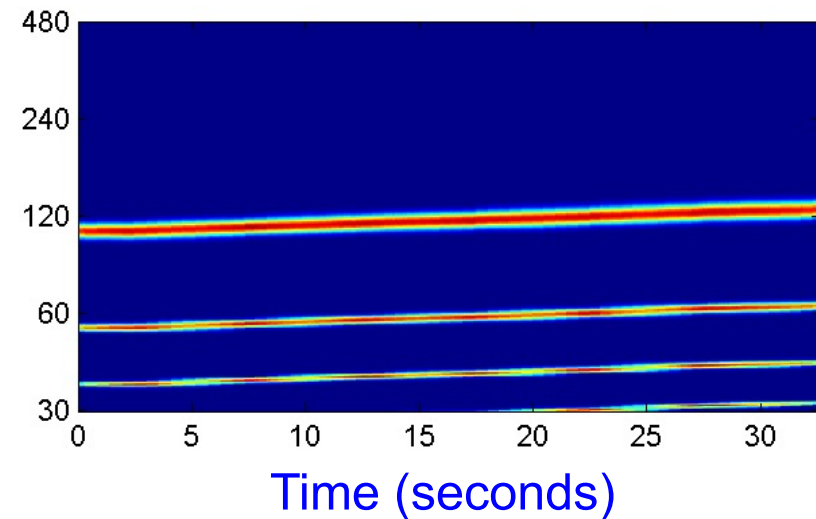
Time
(seconds)

Fourier



Emphasis of tempo harmonics
(integer multiples)

Autocorrelation



Emphasis of tempo subharmonics
(integer fractions)

Tempogram (Summary)

Fourier	Autocorrelation
Novelty curve is compared with sinusoidal kernels each representing a specific tempo	Novelty curve is compared with time-lagged local (windowed) sections of itself
Convert frequency (Hertz) into tempo (BPM)	Convert time-lag (seconds) into tempo (BPM)
Reveals novelty periodicities	Reveals novelty self-similarities
Emphasizes harmonics	Emphasizes subharmonics
Granularity increases as tempo increases; Suitable to analyze tempo on tatum and tactus level	Granularity increases as tempo decreases; Suitable to analyze tempo on tatum and measure level