SPE-L1.3

TANDEM-STRAIGHT:

A TEMPORALLY STABLE POWER SPECTRAL REPRESENTATION FOR PERIODIC SIGNALS AND APPLICATIONS TO INTERFERENCE-FREE SPECTRUM, F0, AND APERIODICITY ESTIMATION

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Outline

- Reformulation of STRAIGHT
  (F0 adaptive time-frequency representation)
  - Power spectrum without temporal variations
    TANDEM
  - Consistent sampling for spectral envelope recovery
    STRAIGHT
- Unified approach based on TANDEM and STRAIGHT
  (F0 and aperiodicity detection)

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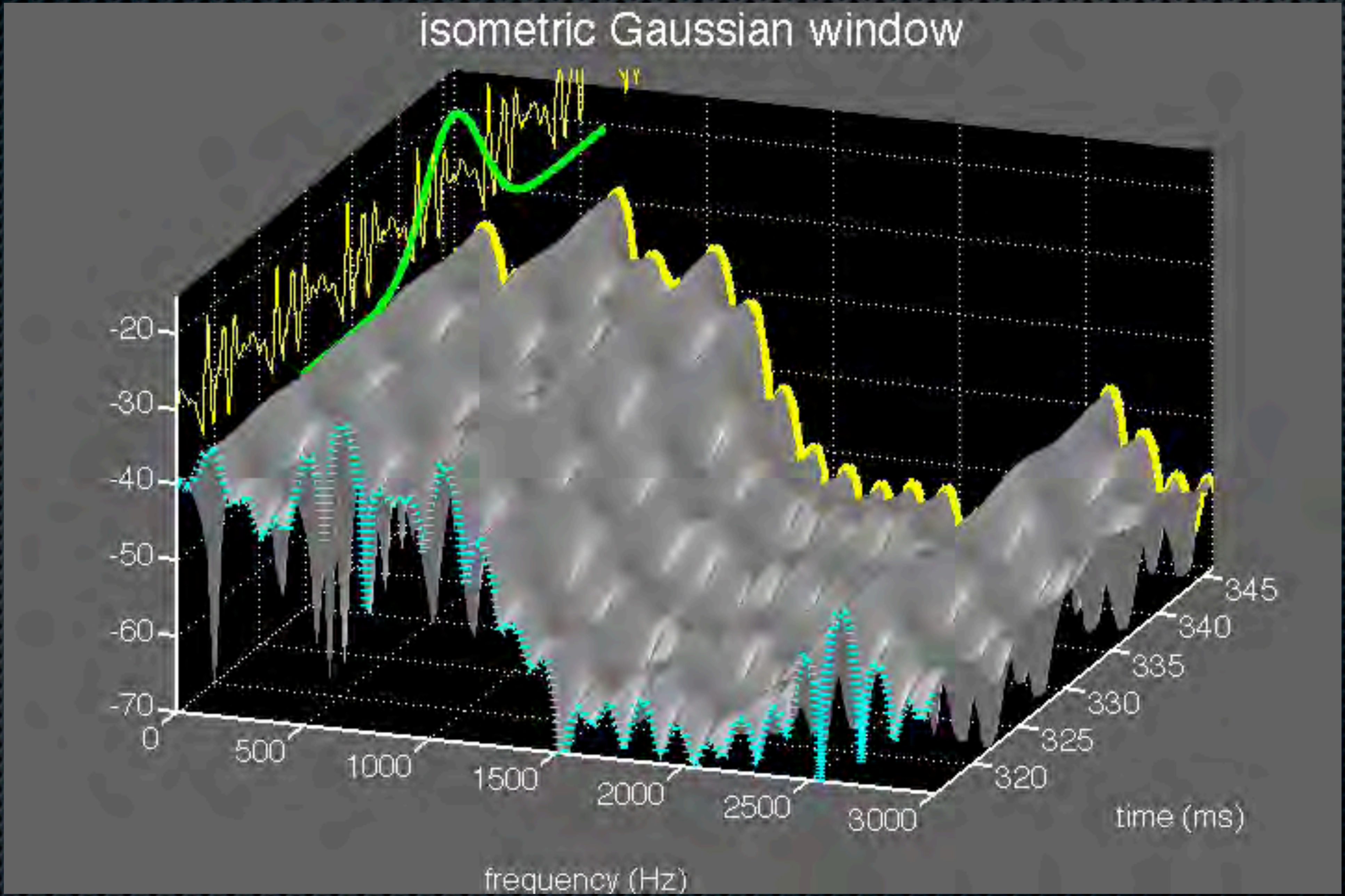
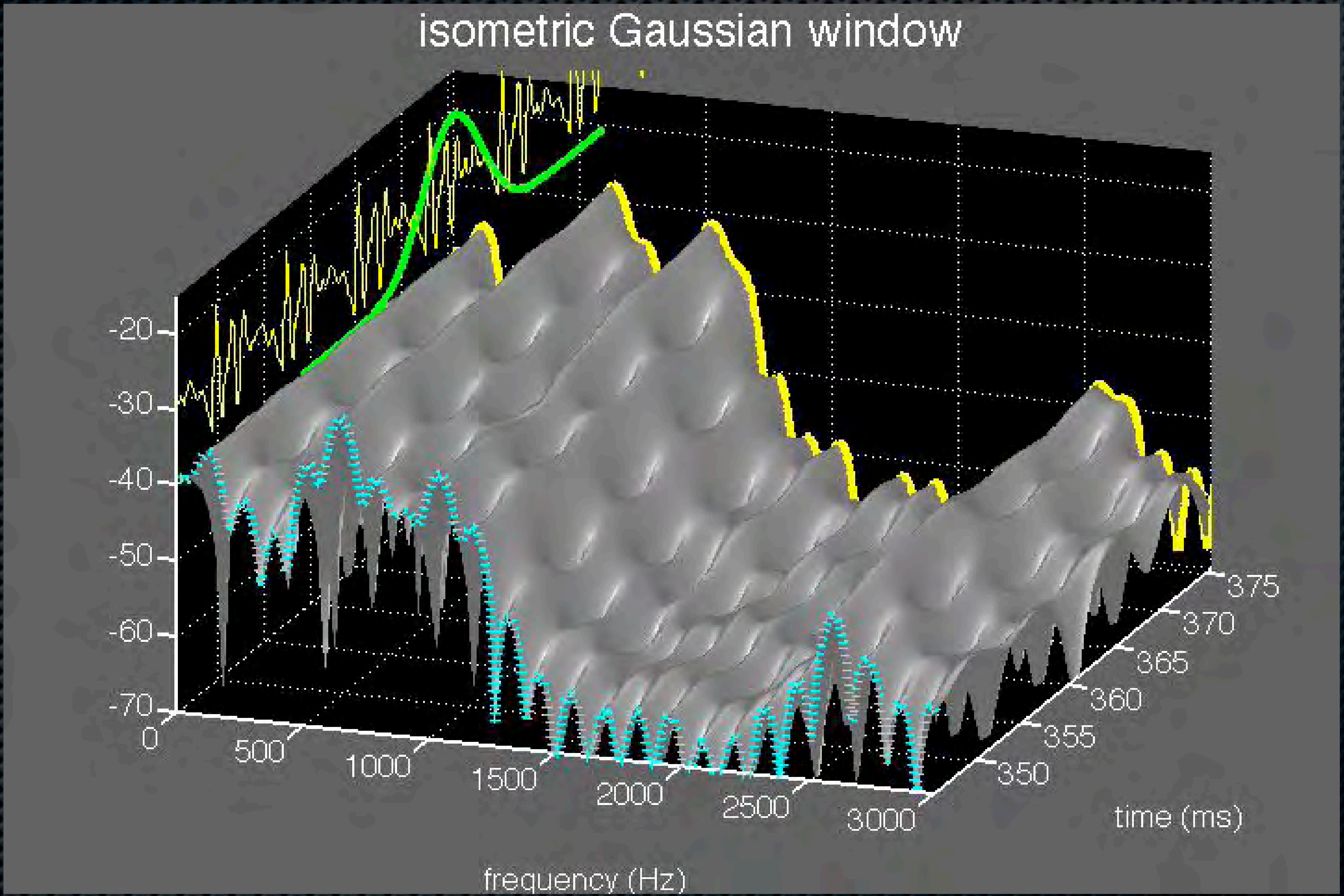
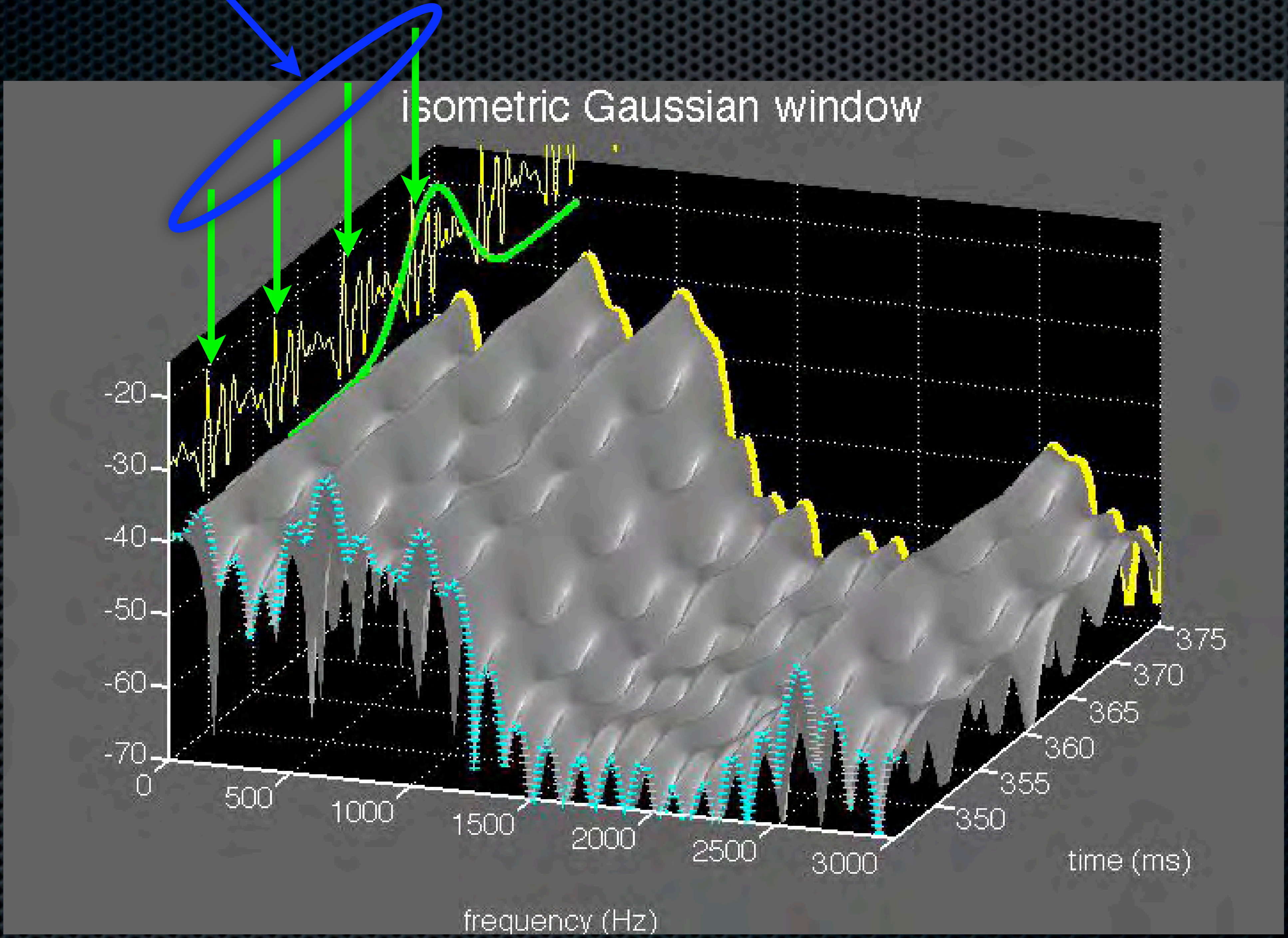
SFT-based spectrogram



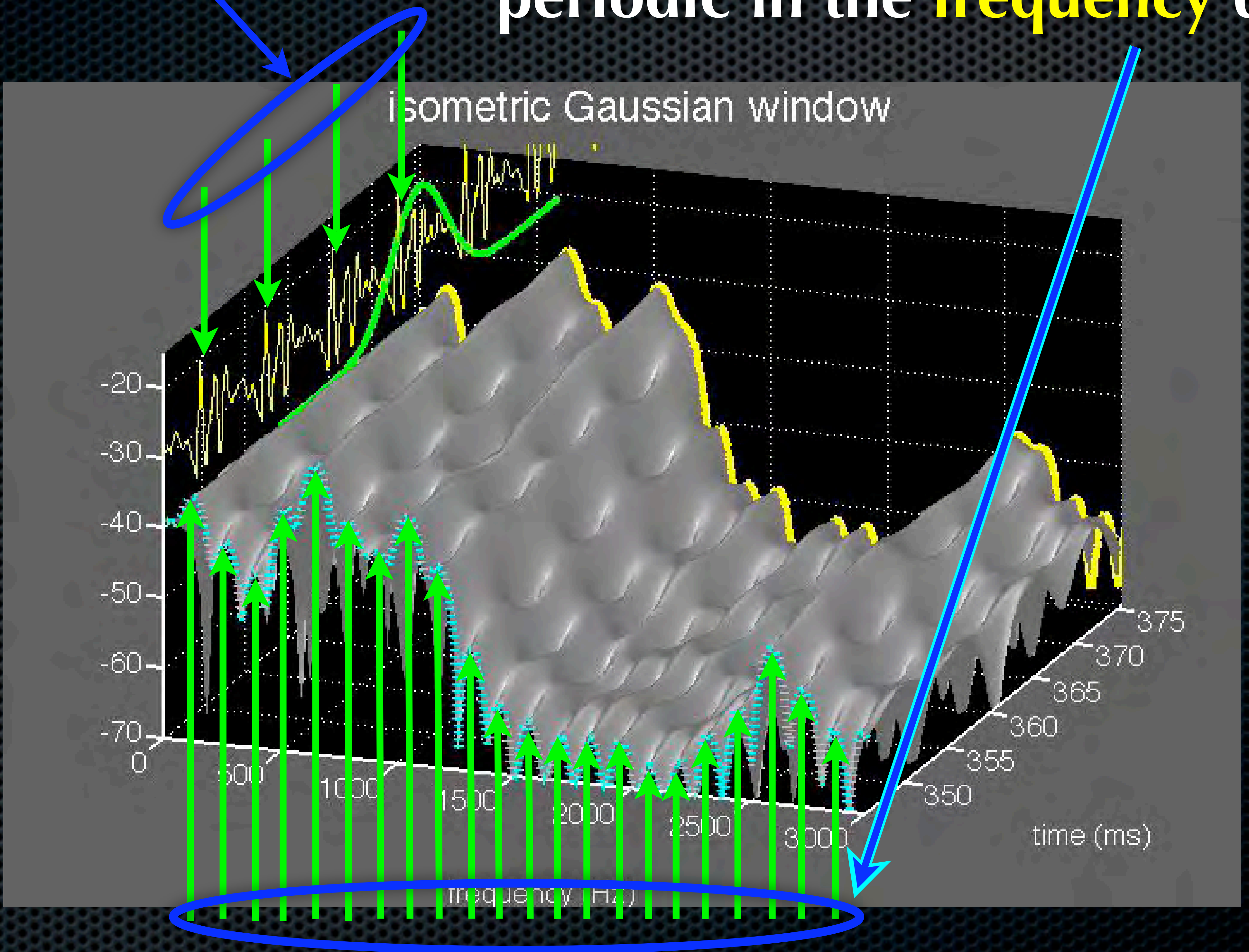

isometric Gaussian window
-20
-30
-40
-50
-60
-70
0
500
1000
1500
2000
2500
3000
frequency (Hz)
350
355
360
365
370
375
time (ms)

periodic in the time domain

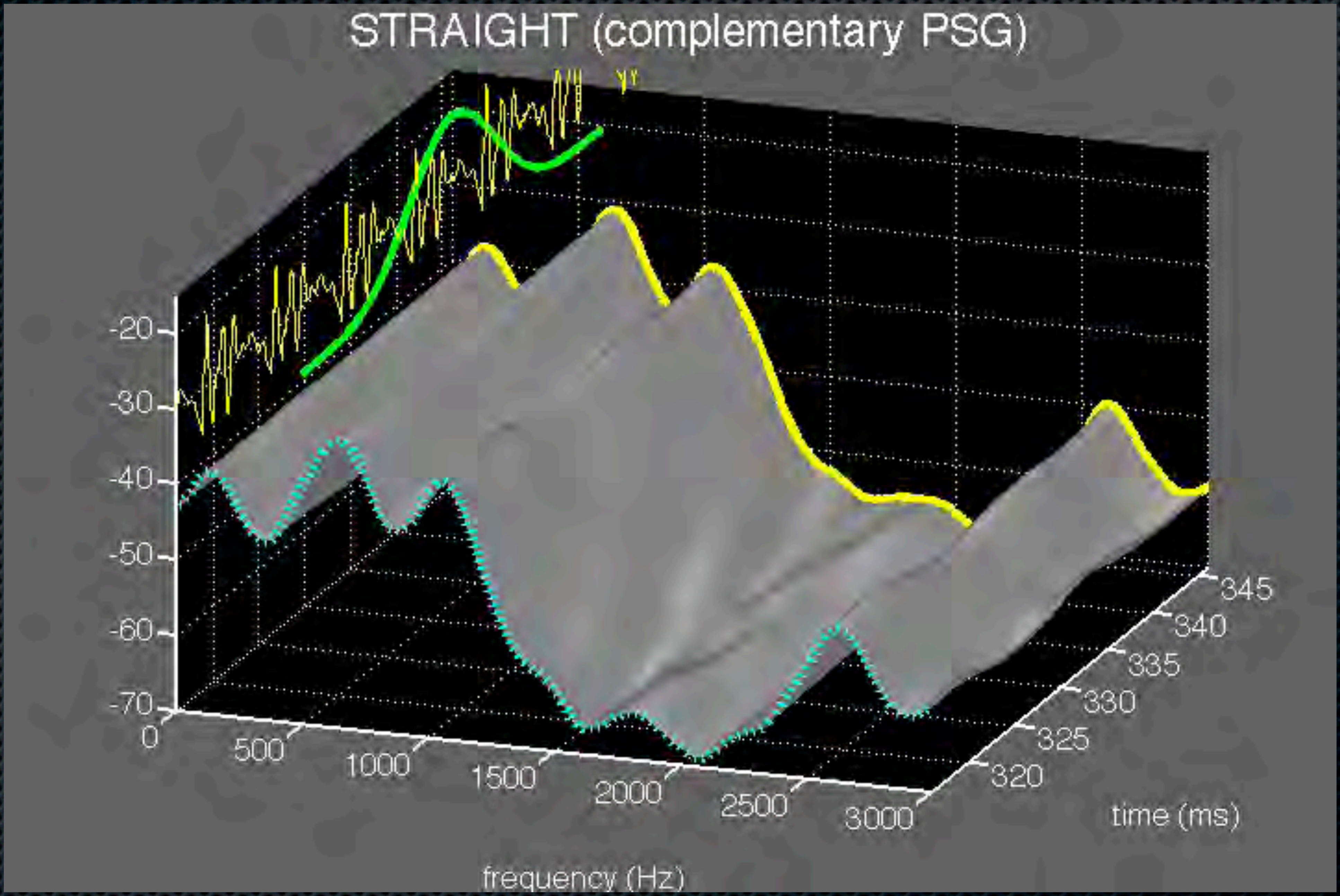


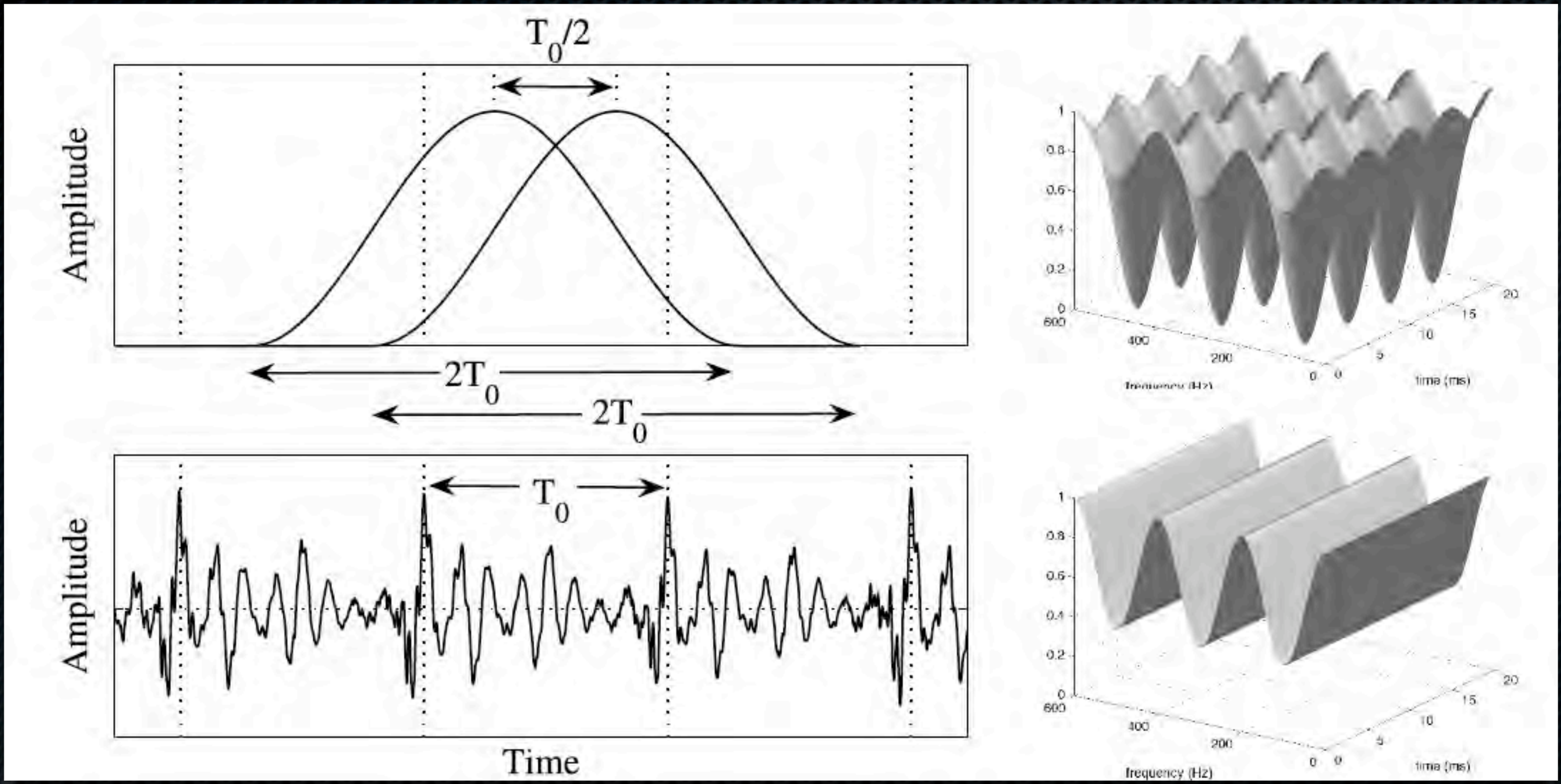
periodic in the **time** domain

periodic in the **frequency** domain



Spline-based optimum smoothing reconstructs the underlying smooth time-frequency representation





TANDEM spectrum

Power spectrum estimation without periodic variations

TANDEM: assumption

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- Time window has low level side lobes.

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$$\delta(\omega) + \alpha e^{j\beta}\delta(\omega - \omega_0)$$

$$\begin{aligned}|S(\omega,\tau)|^2 &= H^2(\omega) + \alpha^2 H^2(\omega - \omega_0) \\ &\quad + 2\alpha H(\omega) H(\omega - \omega_0)\cos(\omega_0\tau + \beta)\end{aligned}$$

$$|S(\omega,\tau)|^2 + |S(\omega,\tau + T_0/2)|^2$$

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signal model

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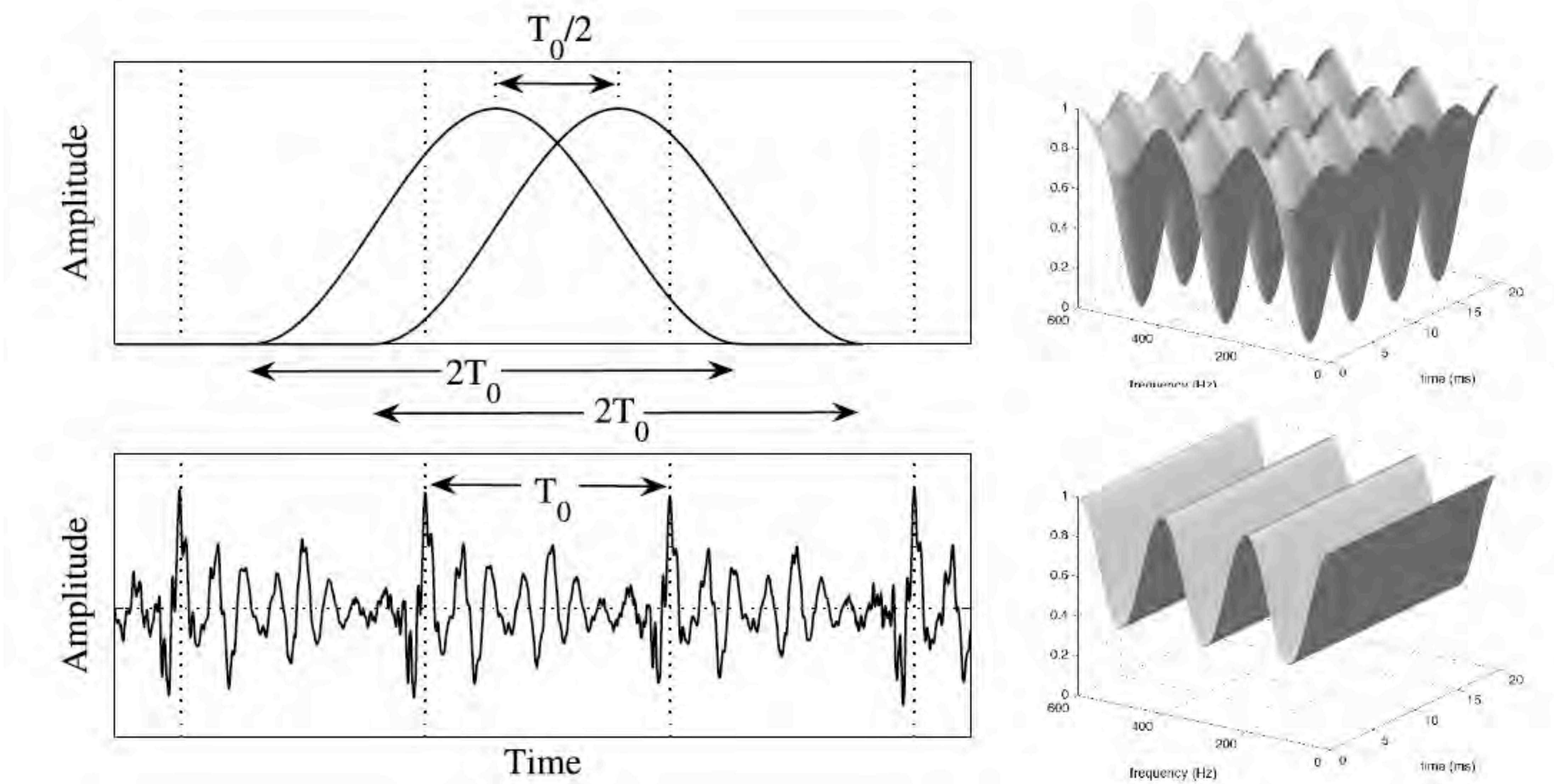
periodic variation

$$|S(\omega,\tau)|^2 + |S(\omega,\tau + T_0/2)|^2$$

TANDEM spectrum

- Calculate power spectra of T0/2 apart and then average them.



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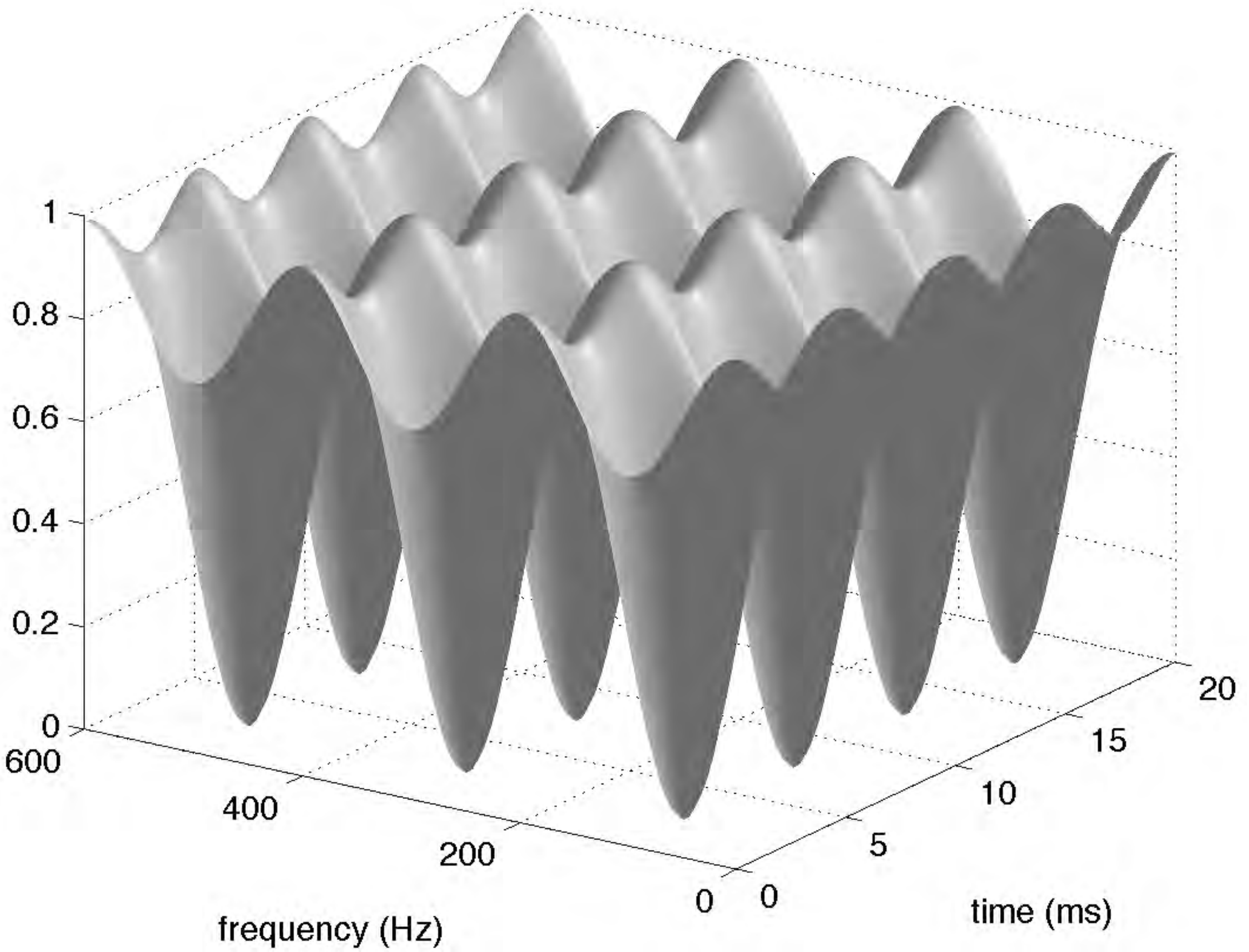
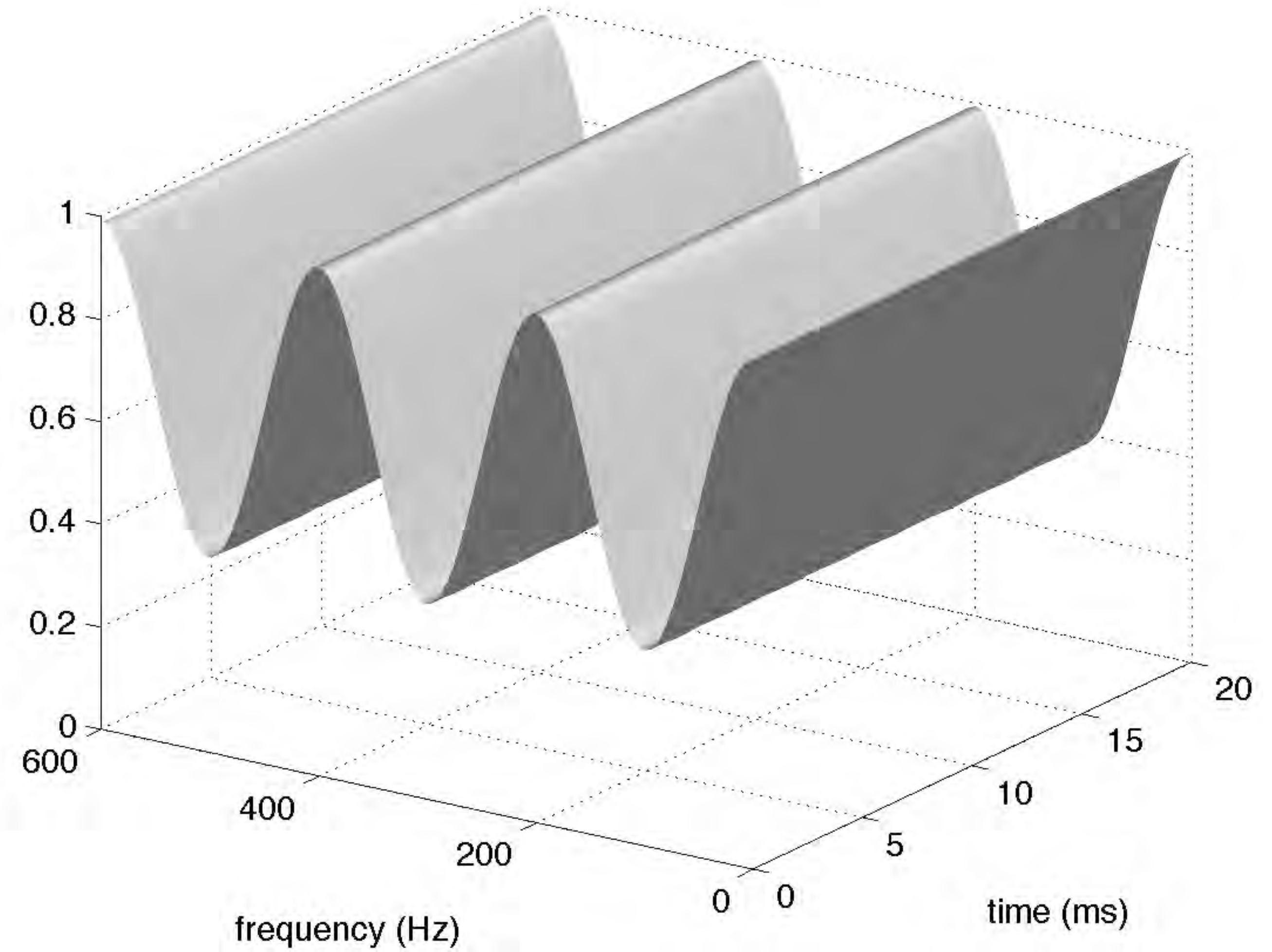
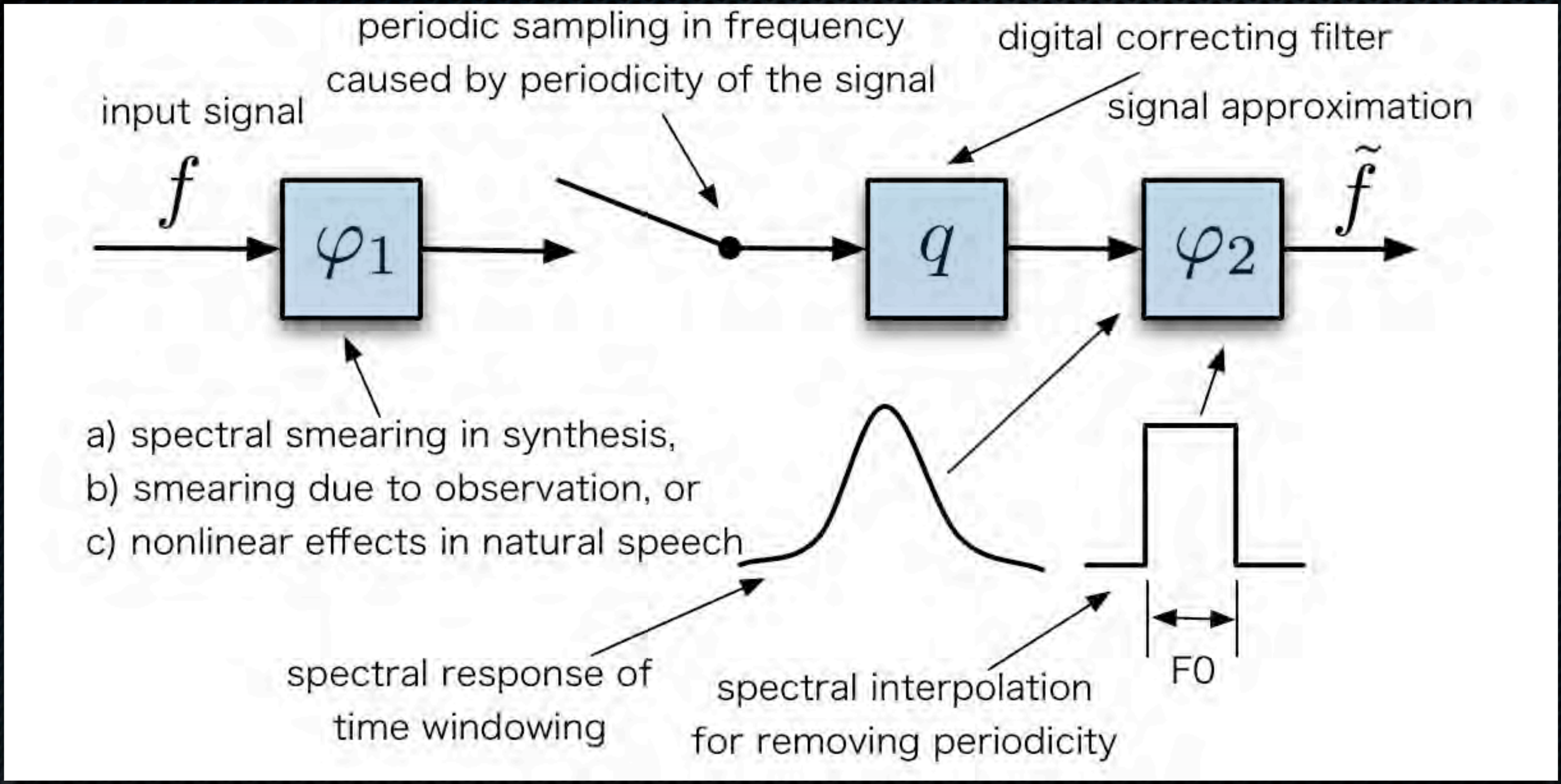




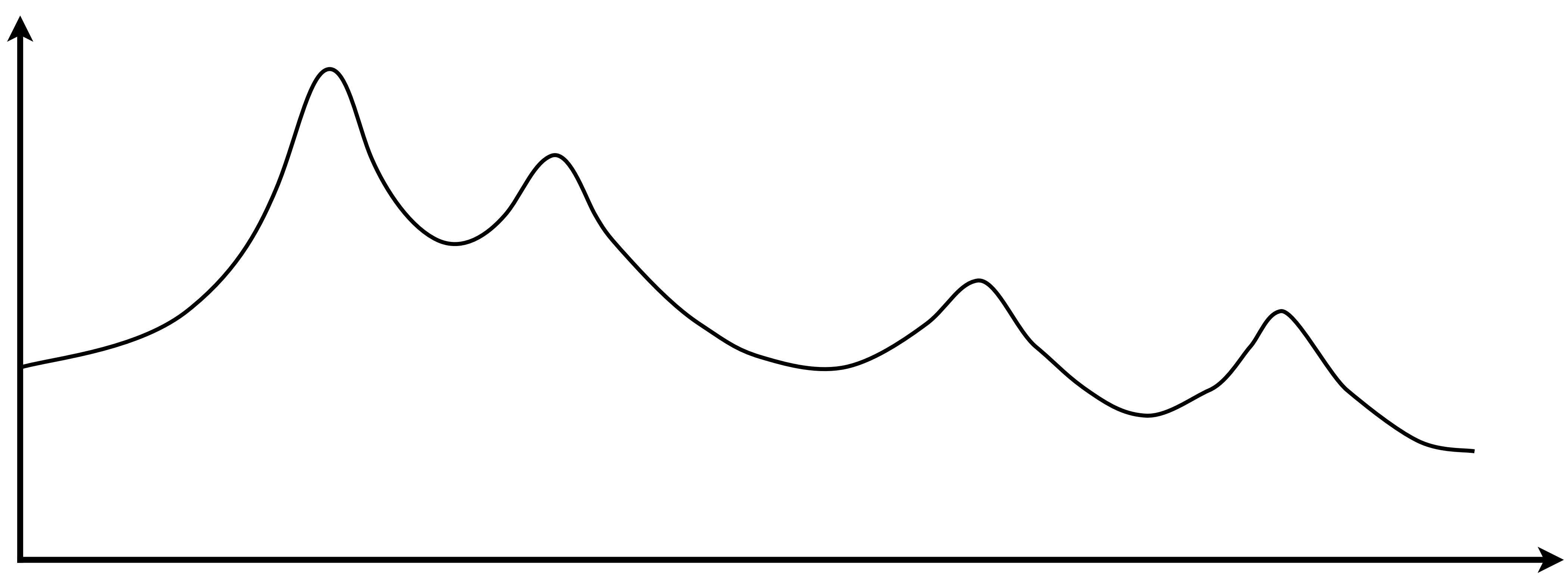


STRAIGHT spectrum

Reformulation based on consistent sampling

Vowel spectral model

- Periodic sampling also in the frequency domain
  - Continuous spectrum has to be recovered from sampled values (D/A conversion)



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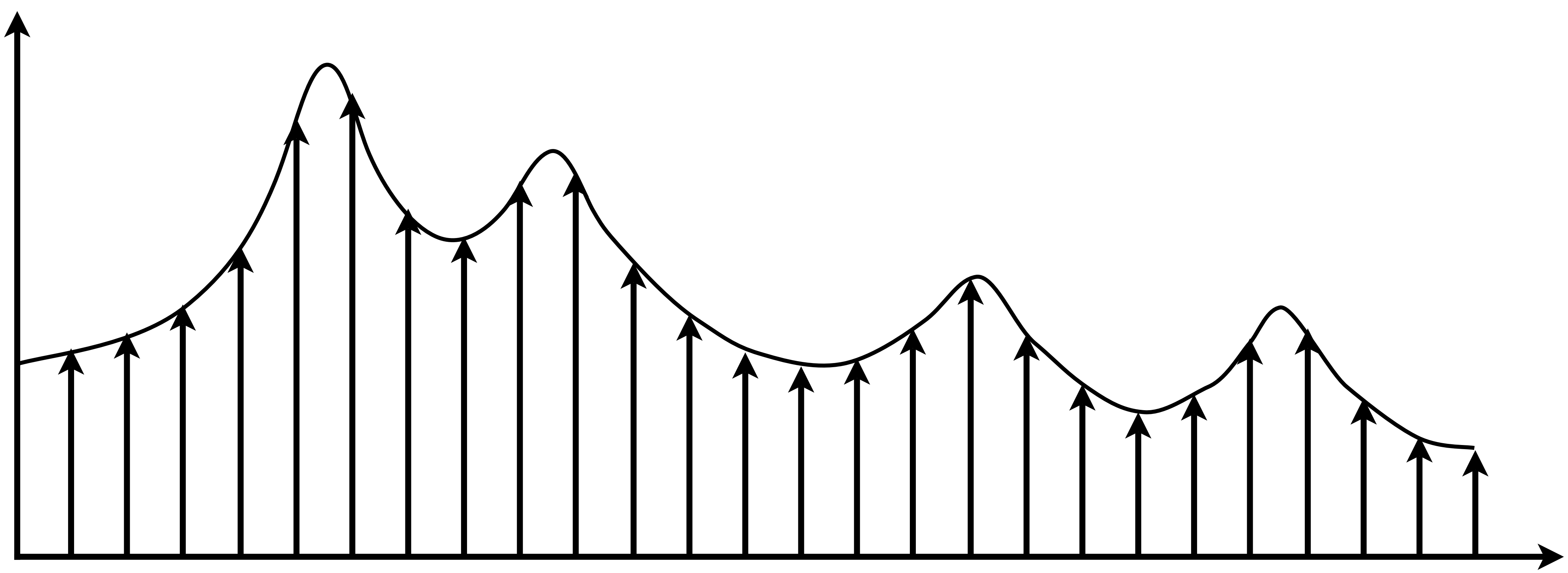

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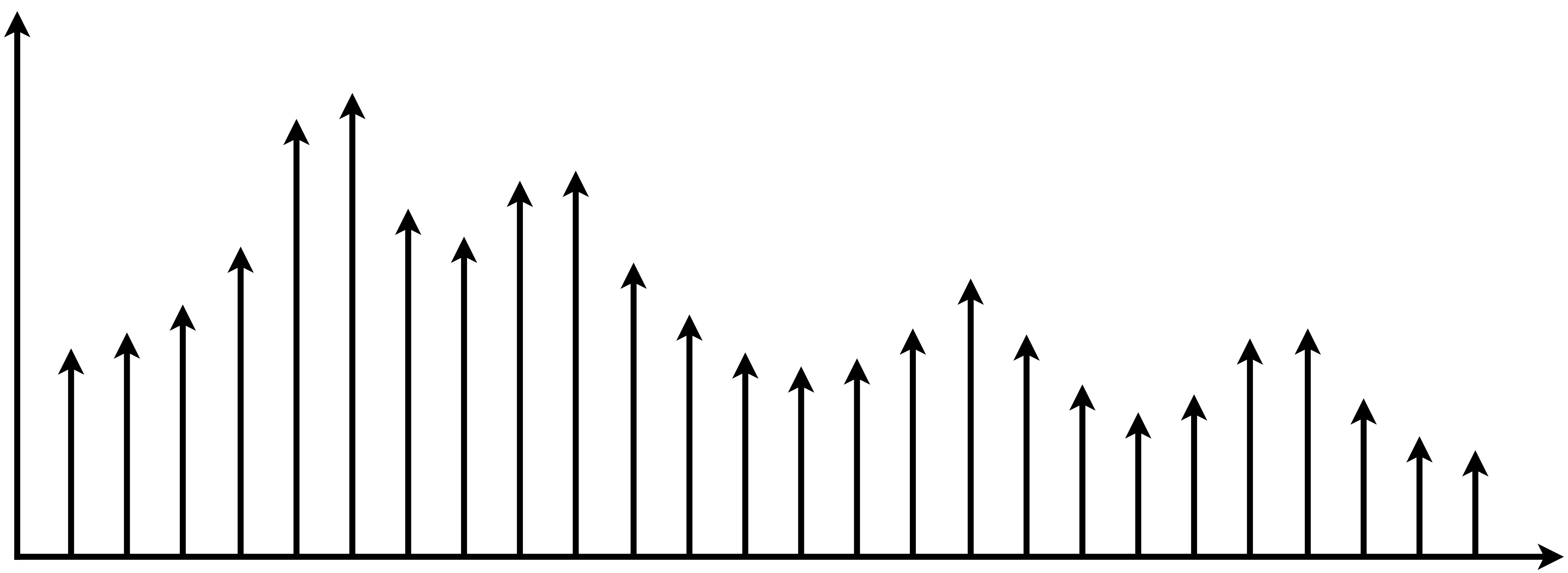

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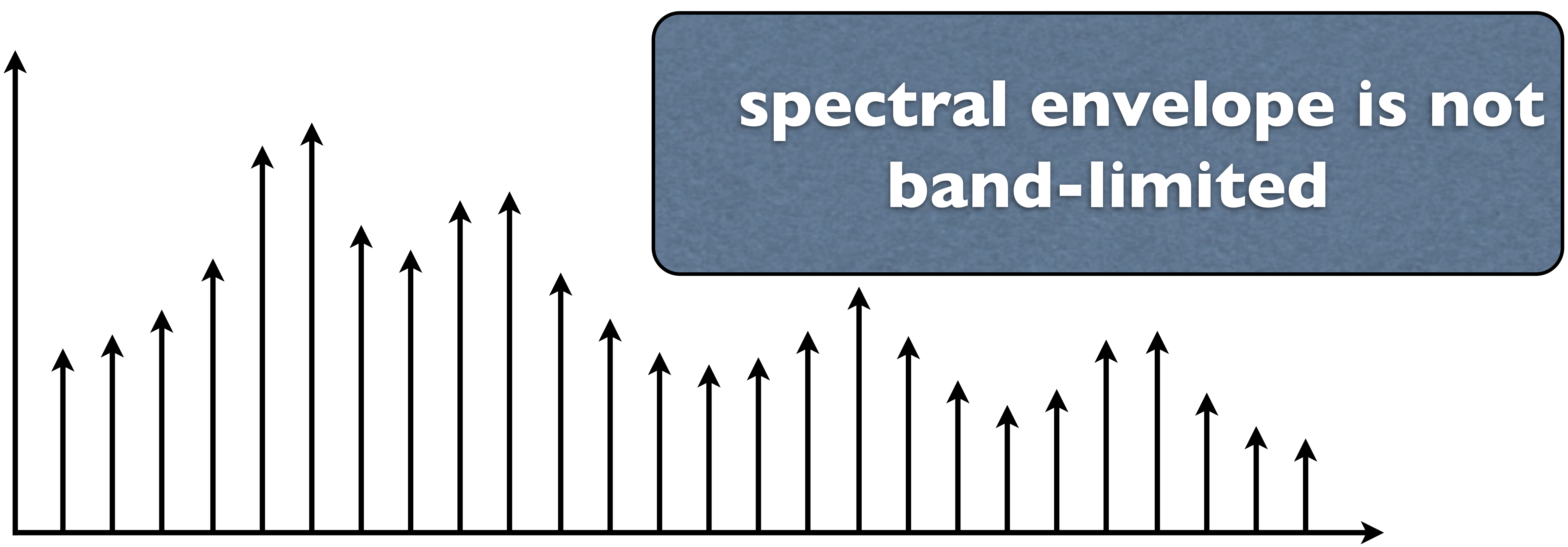
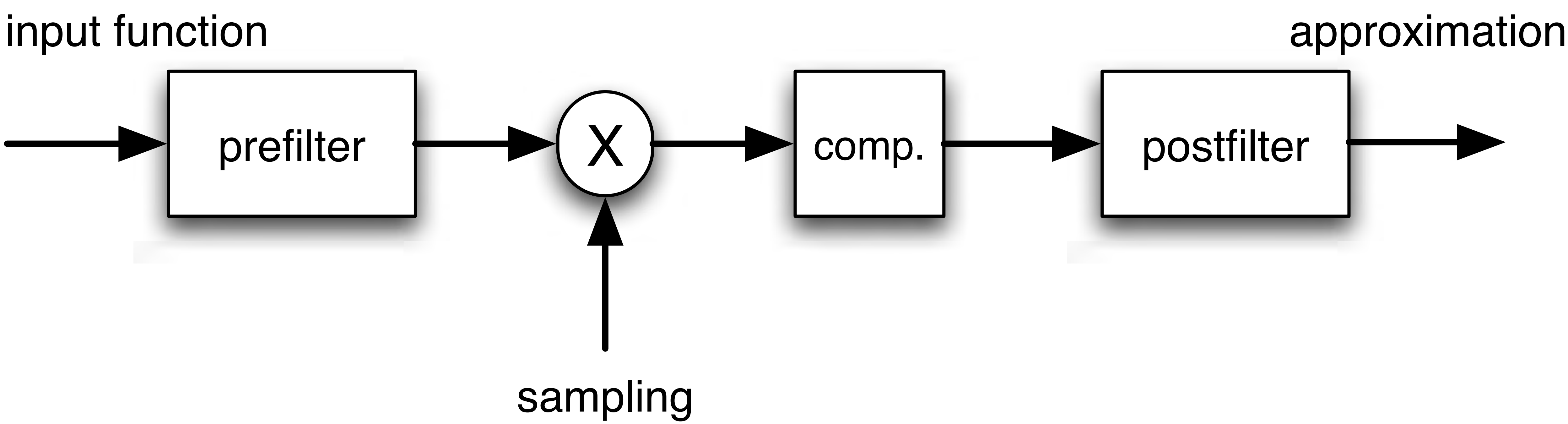


Consistent sampling

- Does not require perfect reconstruction
  - Resampled value required to be consistent with the initially sampled value



Sampling—50 Years After Shannon

MICHAEL UNSER, FELLOW, IEEE PROCEEDINGS OF THE IEEE, VOL. 88, NO. 4, APRIL 2000

$$a_{12}(k) = \langle \varphi_1(x-k), \varphi_2(x) \rangle \tag{22}$$

where φ_1 is the analysis function and where φ_2 is the generating (or synthesis) function on the reconstruction side.

Theorem 2 [127]: Let $f \in H$ be an unknown input function. Provided there exists $m > 0$ such that $|A_{12}(e^{j\omega})| \geq m$, a.e., then there is a unique signal approximation $\tilde{f}$ in $V(\varphi_2)$ that is consistent with f in the sense that

$$\forall f \in H,\ c_1(k) = \langle f, \varphi_1(x-k) \rangle = \langle \tilde{f}, \varphi_1(x-k) \rangle. \tag{23}$$

This signal approximation is given by

$$\tilde{f} = \tilde{P} f(x) = \sum_{k \in Z} (c_1 * q)(k) \varphi_2(x-k) \tag{24}$$

where

$$Q(z) = \frac{1}{\sum_{k \in Z} a_{12}(k) z^{-k}} \tag{25}$$

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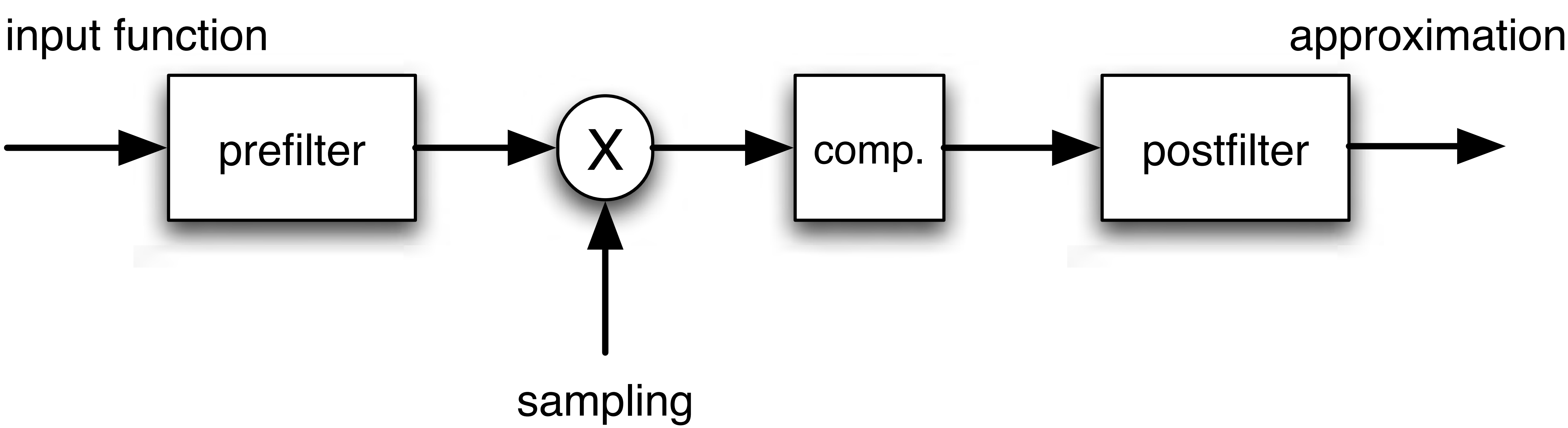

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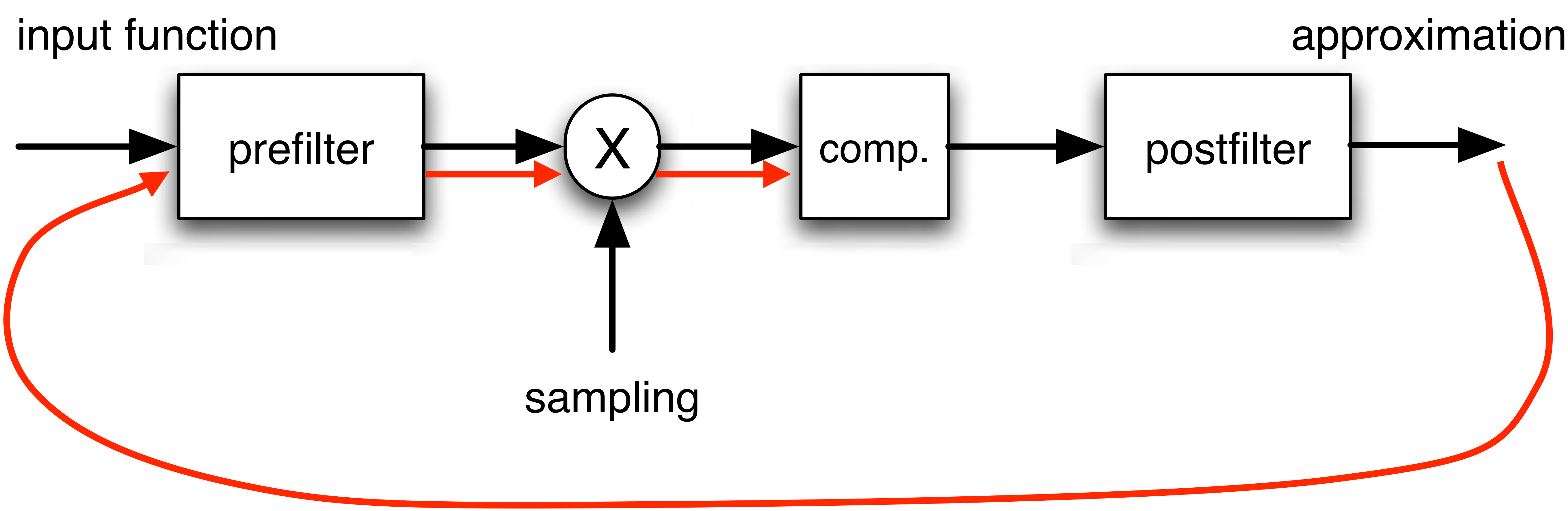

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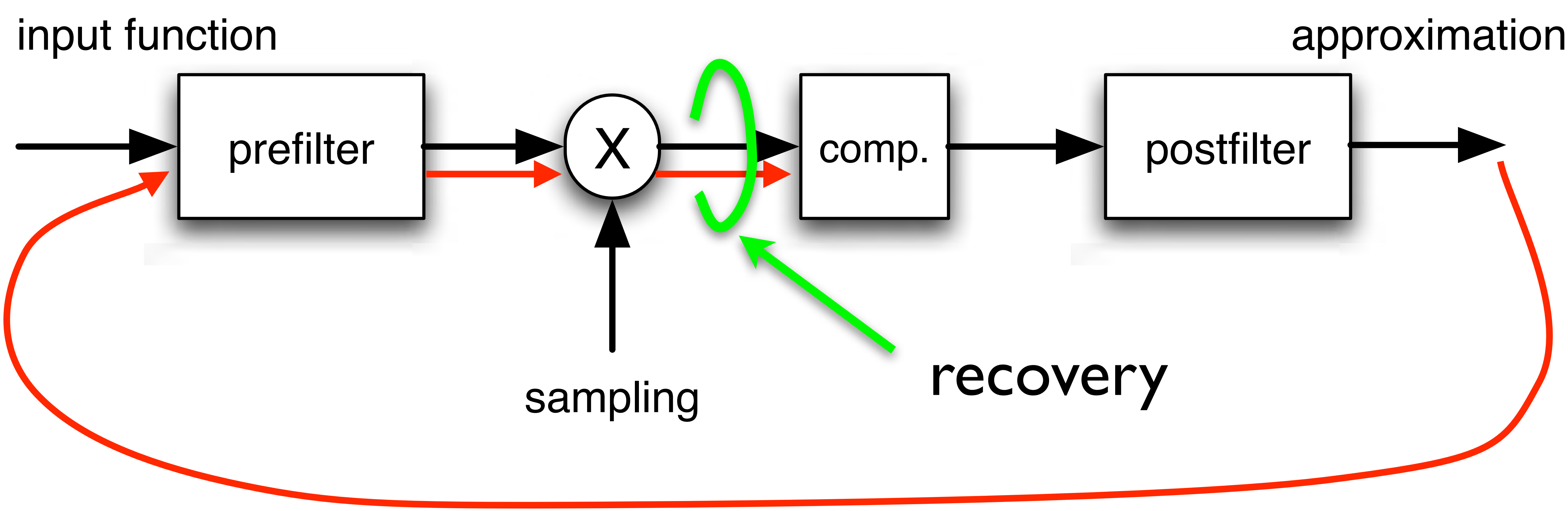

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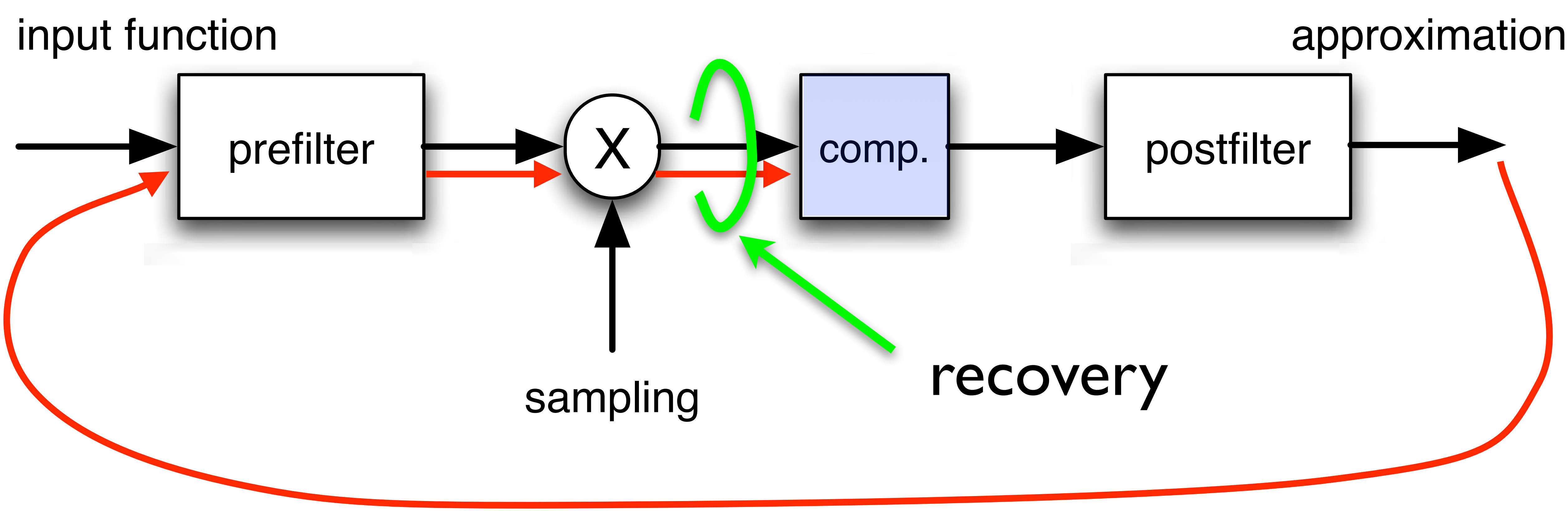

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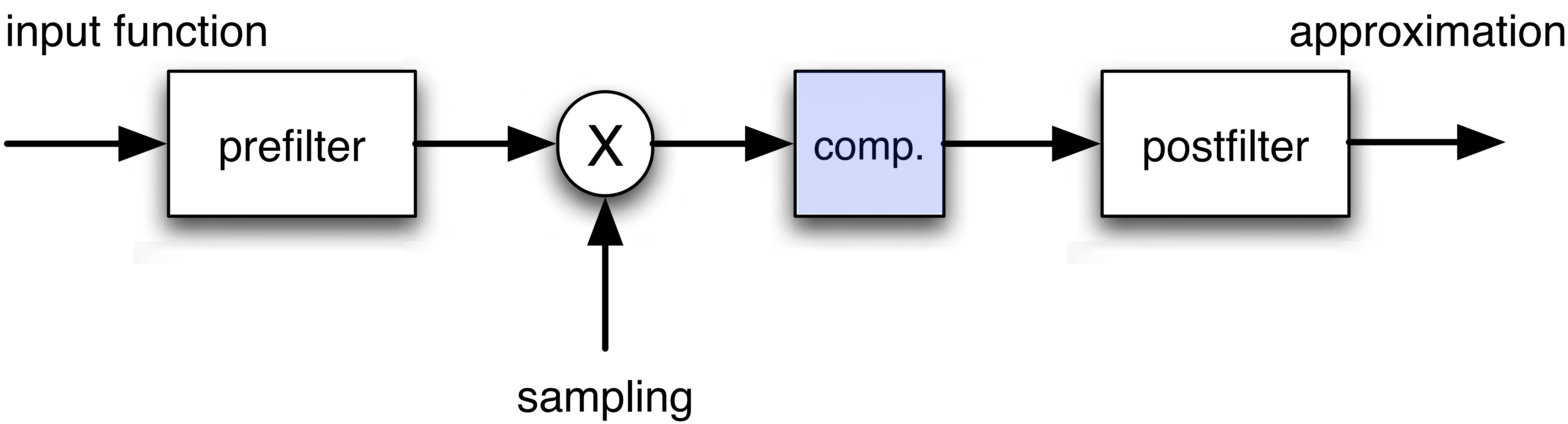

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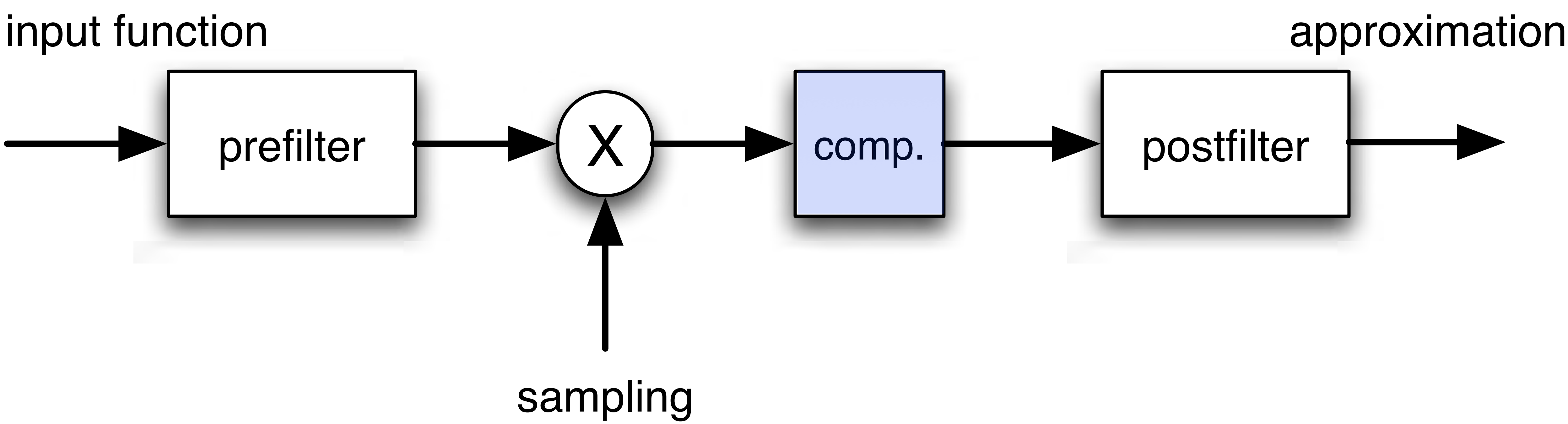

sampling at harmonic frequencies

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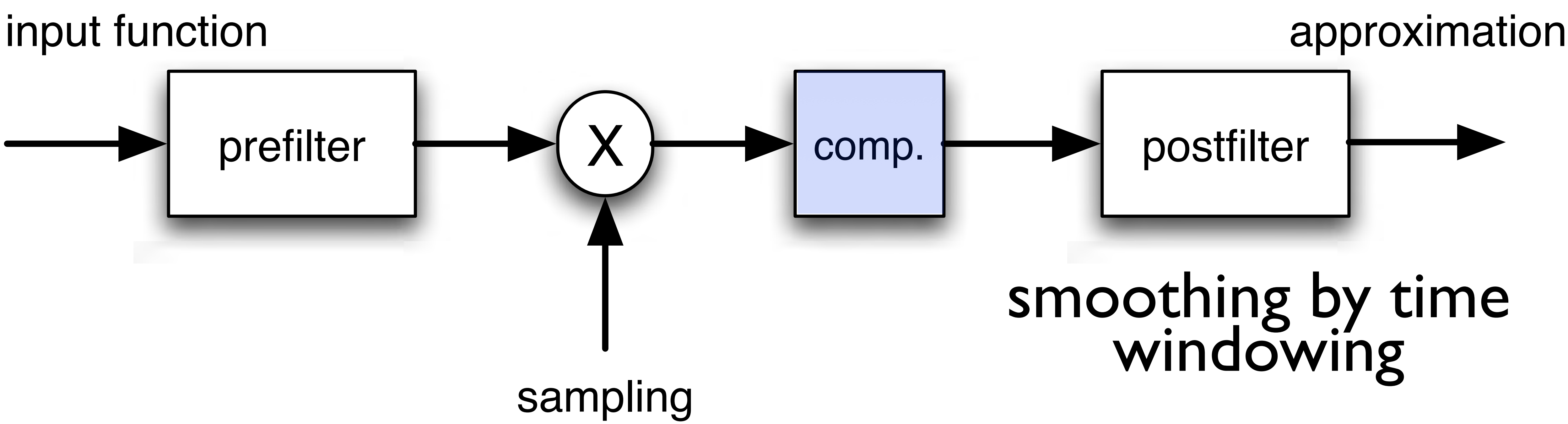

smoothing by time windowing

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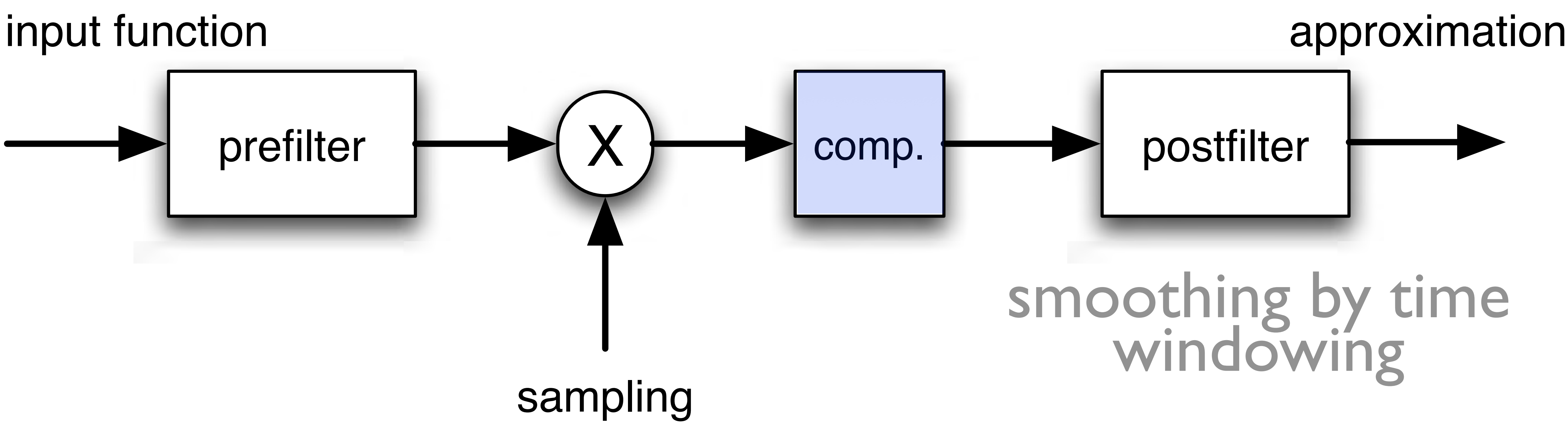

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sampling pulse removal by holding

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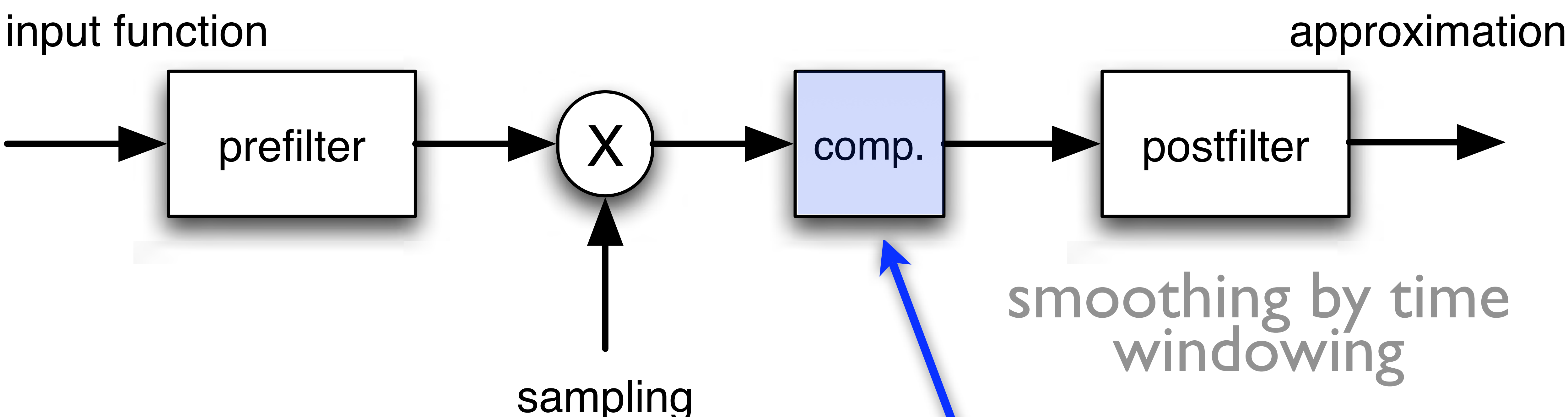

smoothing by time windowing

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sampled value recovery by a compensation filter

A simple implementation

- Holding using cumulative power spectrum and interpolation of differentiation

TANDEM spectrum

$$C(\omega) = \int_{\omega_L}^{\omega} P_T(\lambda) d\lambda$$

$$L_S(\omega) = \ln \left[C(\omega + \omega_0/2) - C(\omega - \omega_0/2) \right] - \ln \omega_0$$

$$P_{TST}(\omega) = e^{[\bar{q}_1 (L_S(\omega - \omega_0) + L_S(\omega + \omega_0)) + \bar{q}_0 L_S(\omega)]}.$$

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holding and interpolation

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- Compensation on log-spectrum to assure results to be positive

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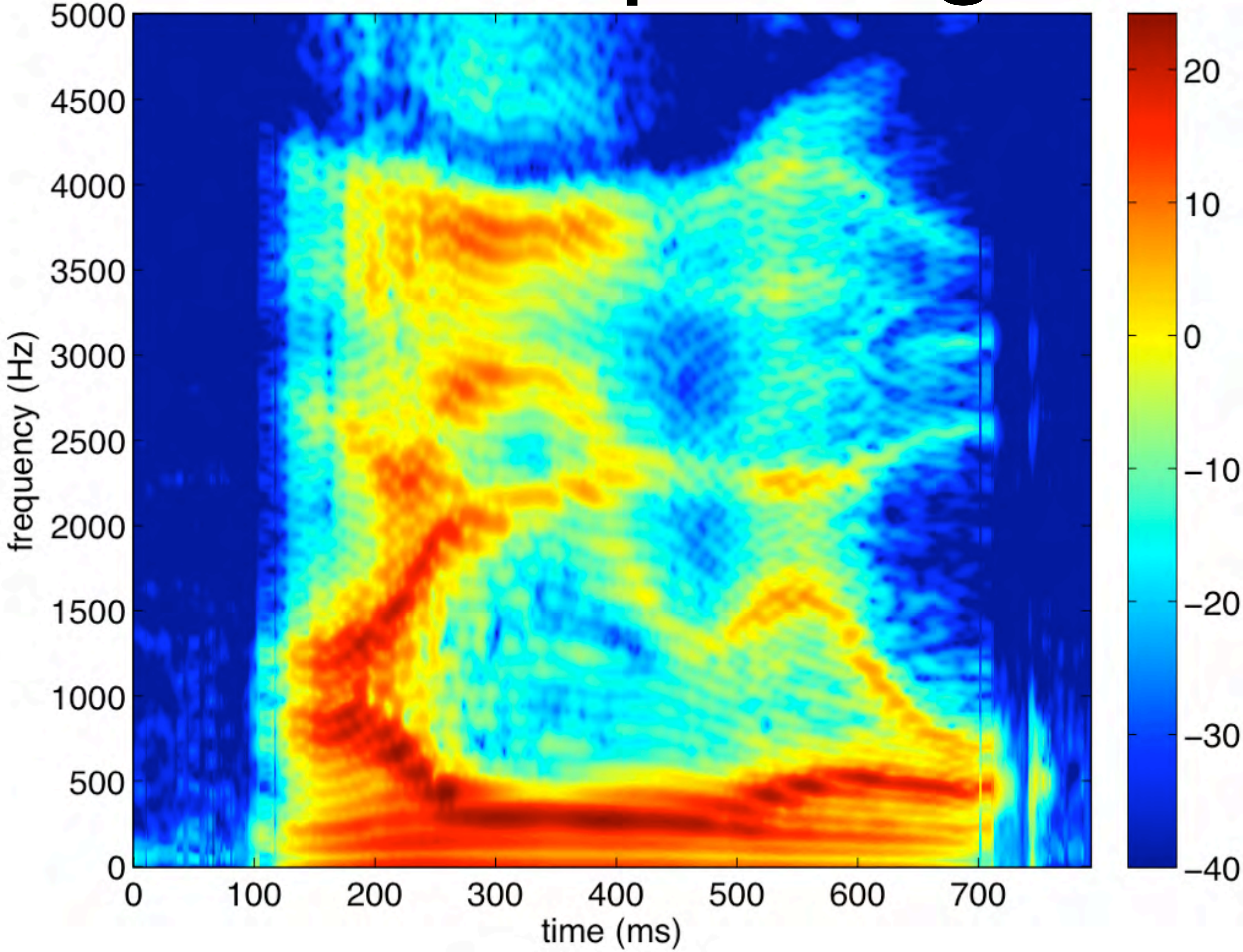
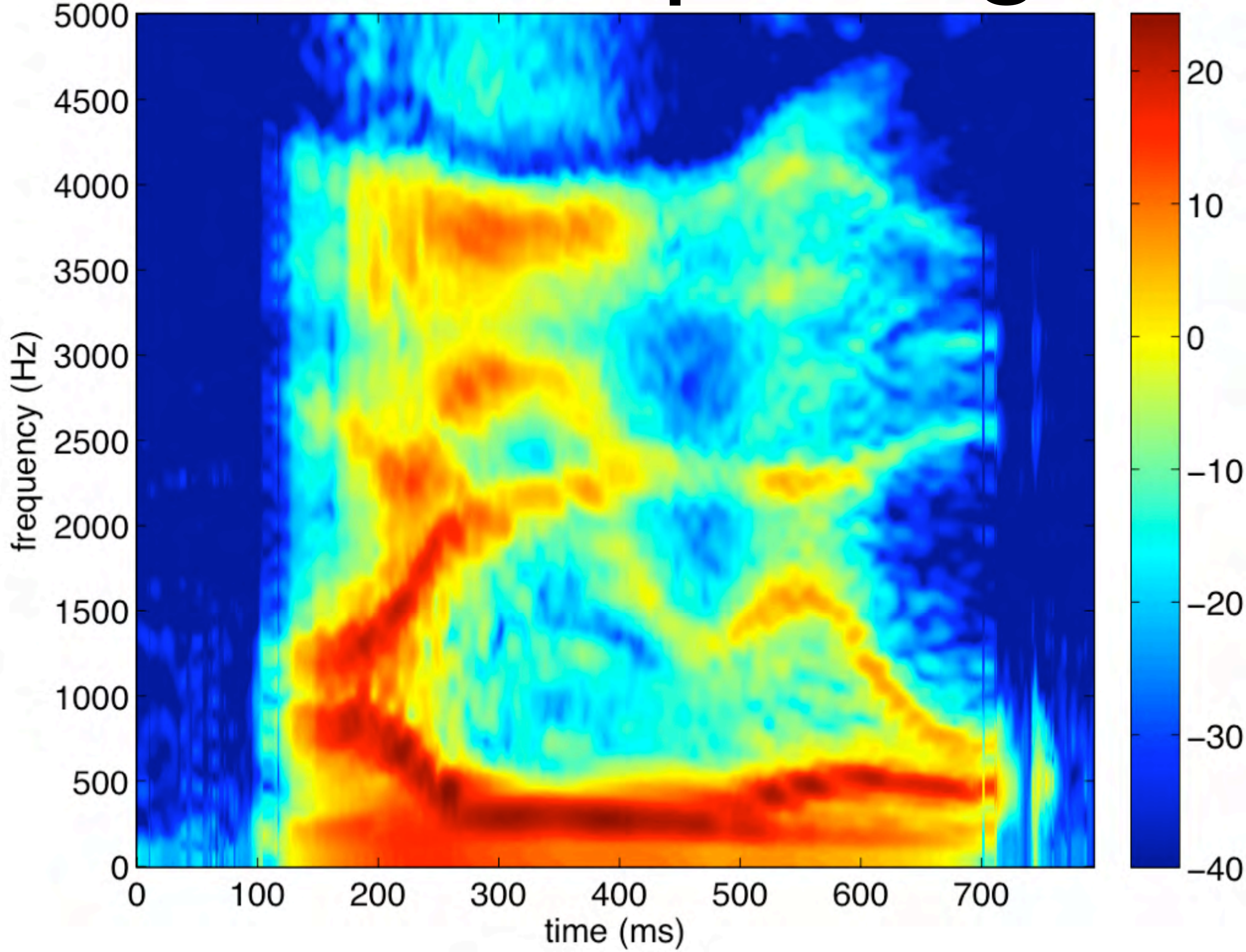
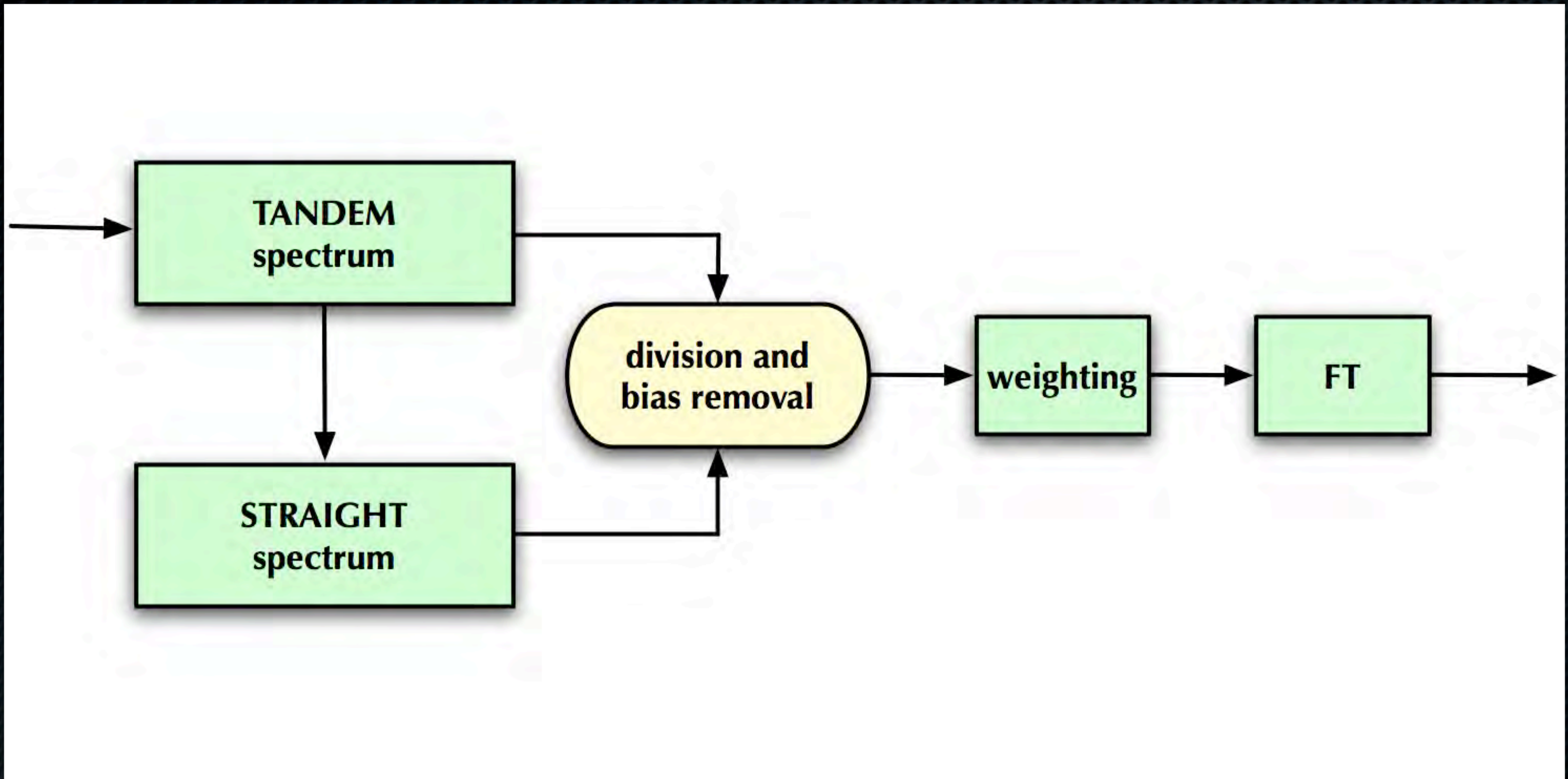
compensation on log-spectrum

TANDEM spectrogram



STRAIGHT spectrogram





Periodicity detection

Unified framework based on TANDEM and STRAIGHT spectra

Application of TANDEM and STRAIGHT to F0 extraction

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variation spectrum

TANDEM spectrum

$$P_C(\omega) = \frac{P_T(\omega)}{P_{TST}(\omega)} - 1$$

STRAIGHT spectrum

How does it behave?

How does it behave?

- Band-pass filtering in the spatial frequency domain

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- Band-pass filtering in the spatial frequency domain
  - Time windowing --> low pass

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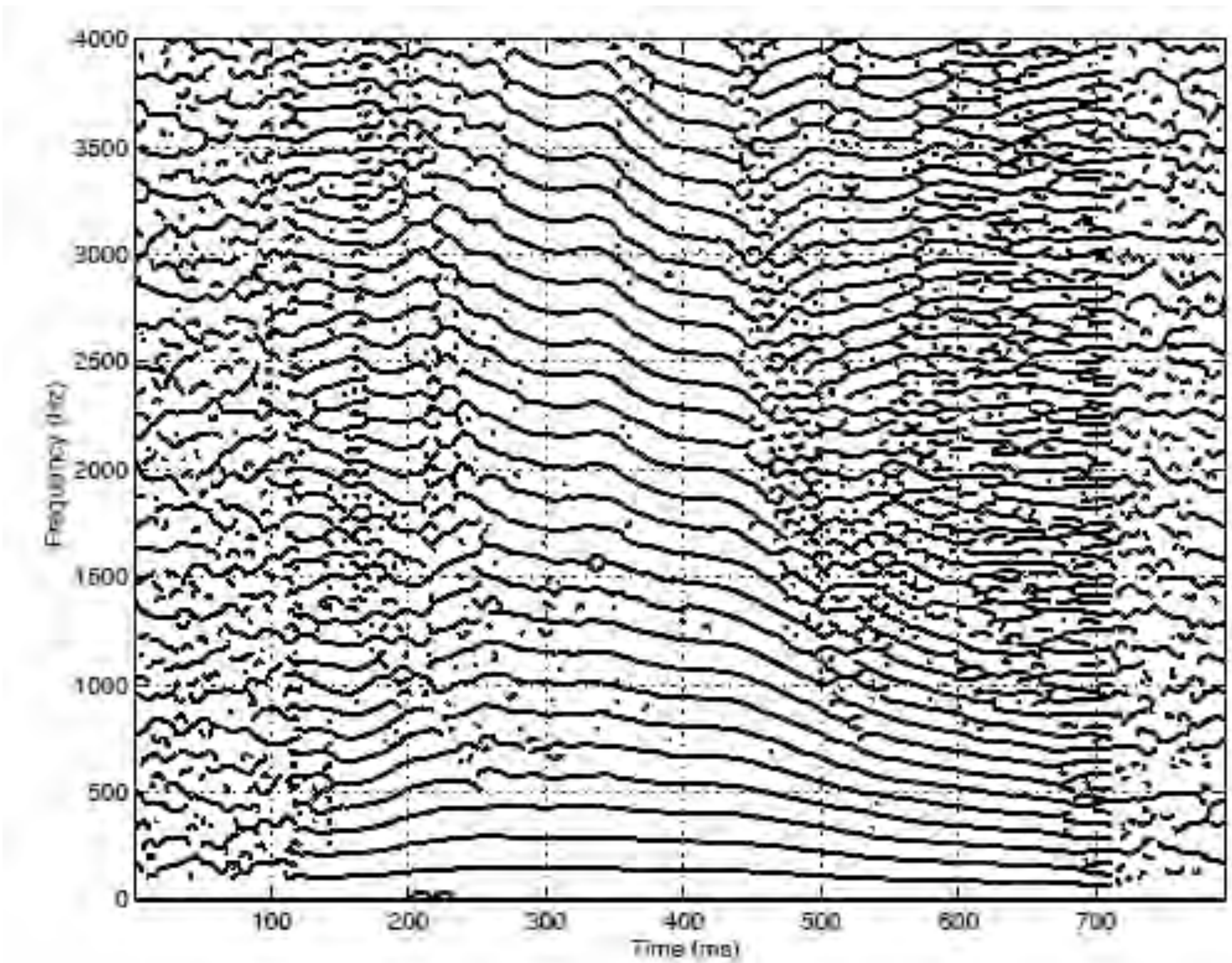
  - Variation spectrum --> high pass
  - Band-pass response --> tunable to F0

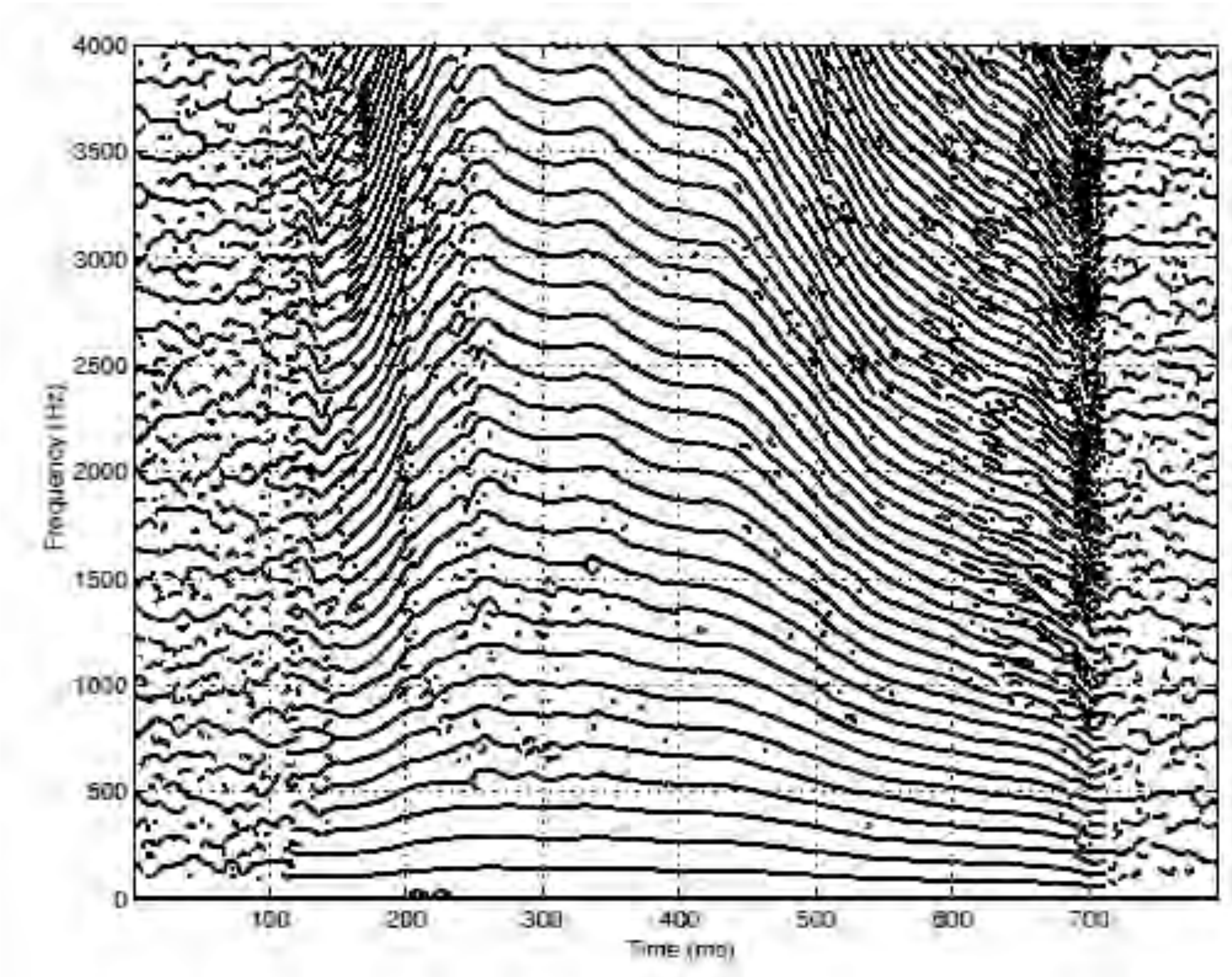
How does it behave?

- Band-pass filtering in the spatial frequency domain
  - Time windowing --> low pass
  - Variation spectrum --> high pass
  - Band-pass response --> tunable to F0
- In the higher (original) frequency region, harmonic structure is corrupted by moire effects

Moire effects



Moire effects



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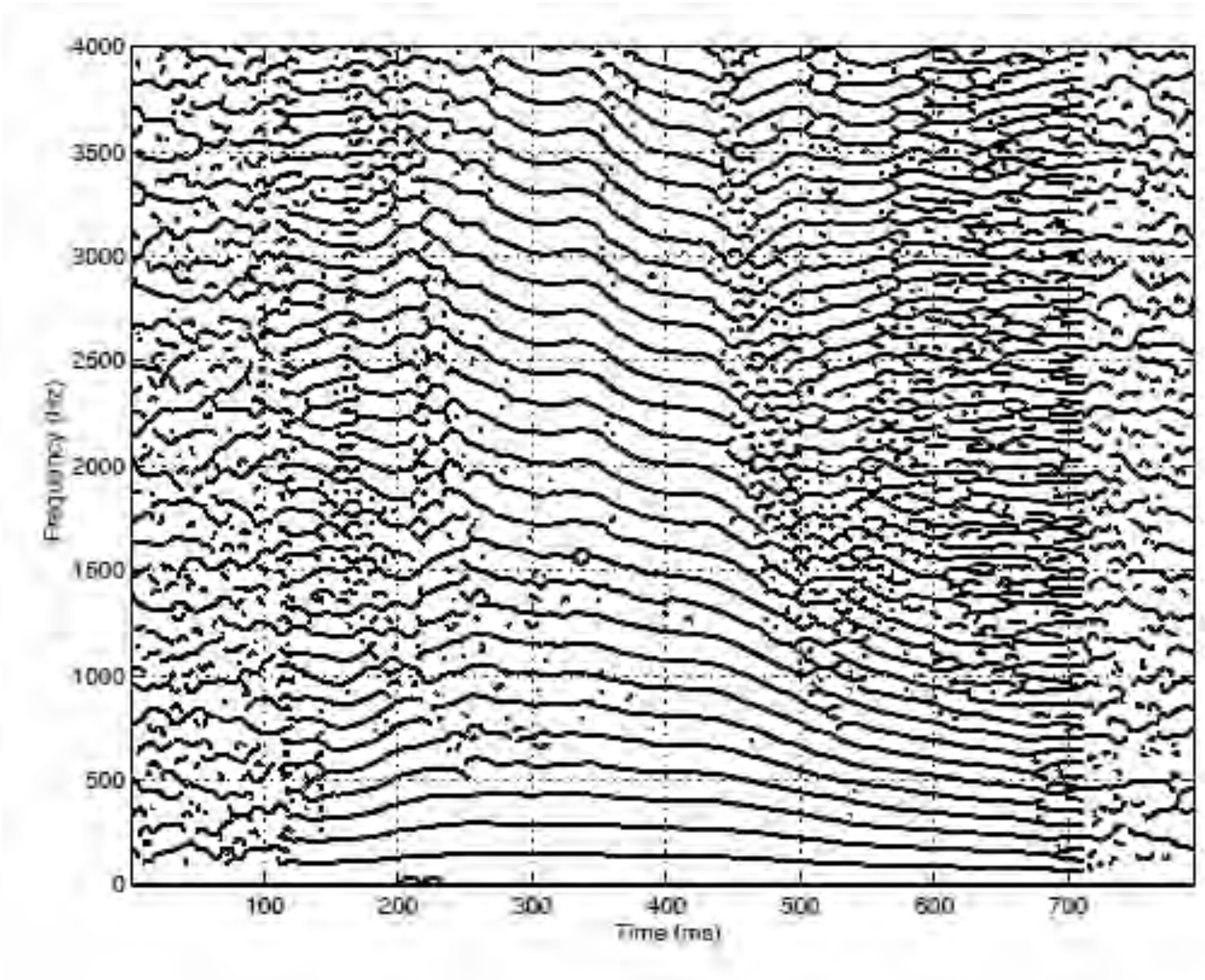

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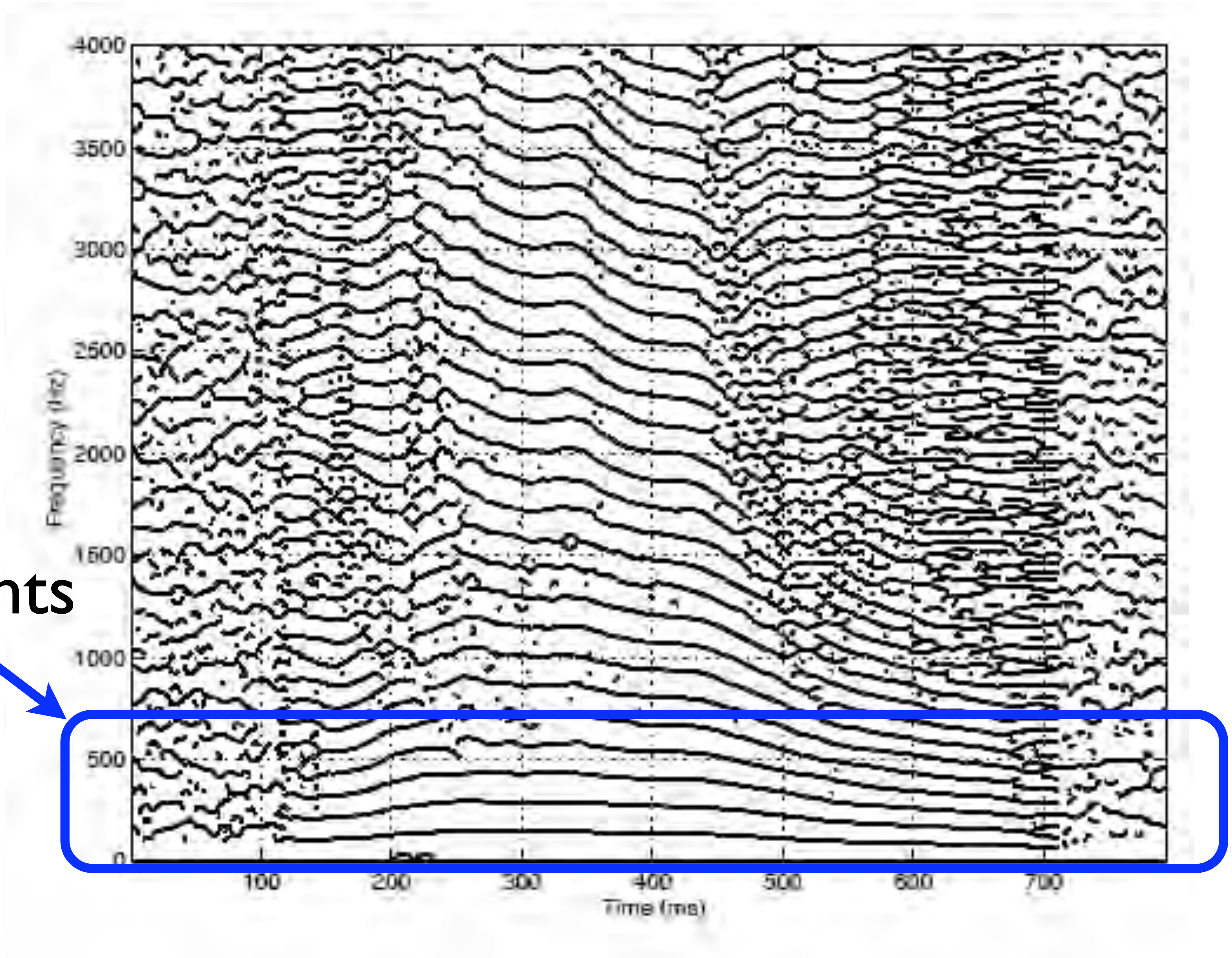
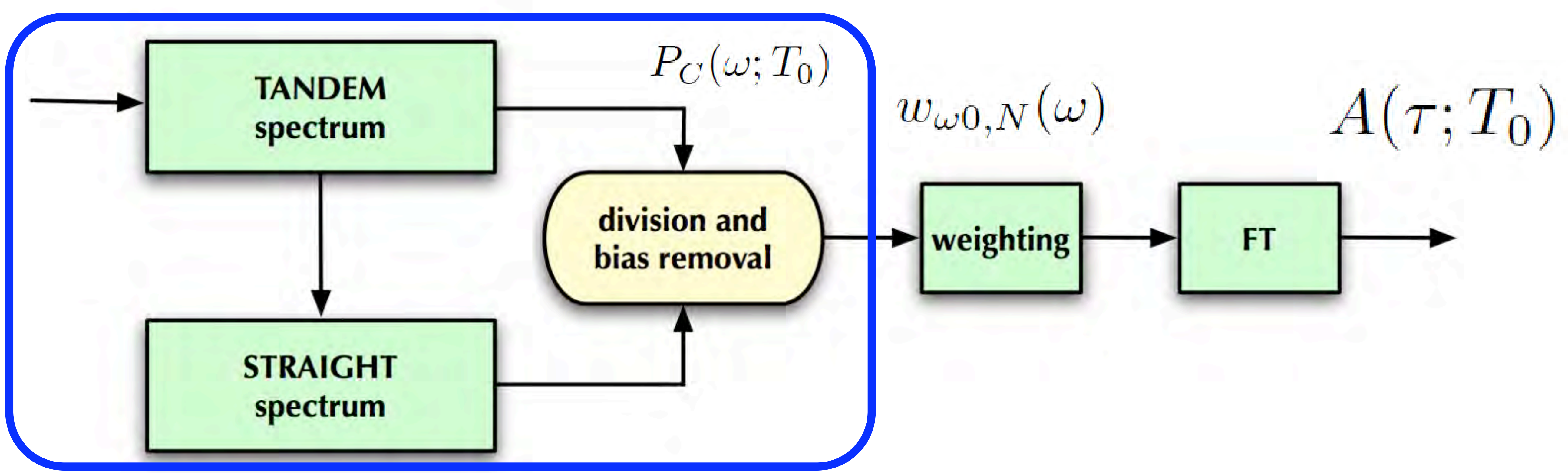


reliable components

F0 tuned F0 detector



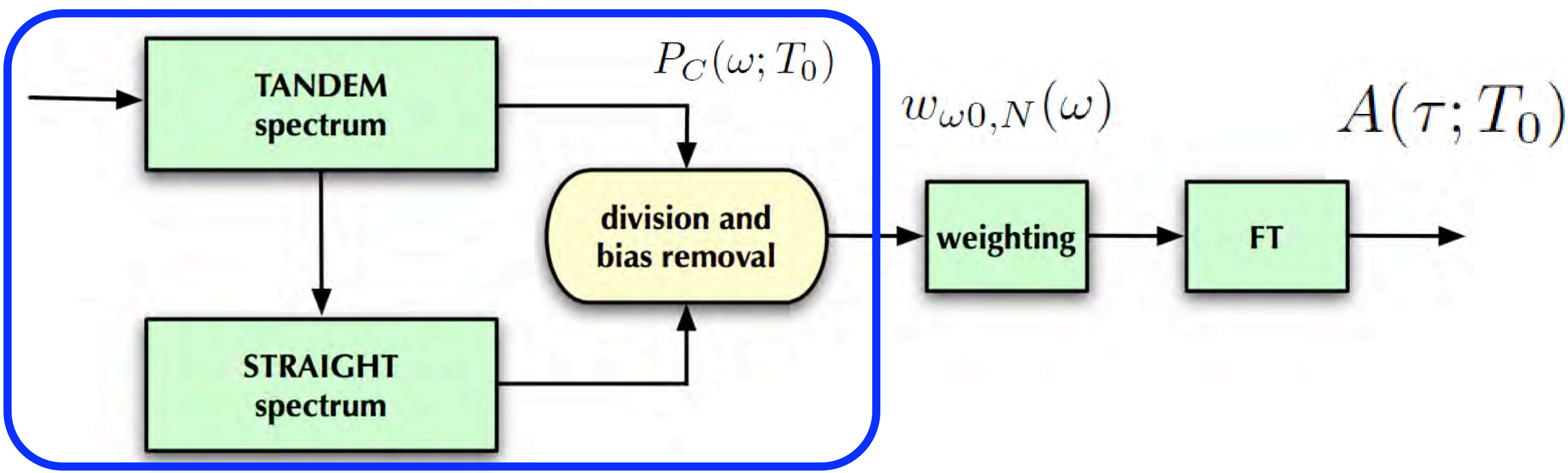
F0 tuned F0 detector

spatial frequency component

$$A(\tau; T_0) = \int_{-\infty}^{\infty} w_{\omega 0,N}(\omega) P_C(\omega; T_0) e^{-j\omega\tau} d\omega$$

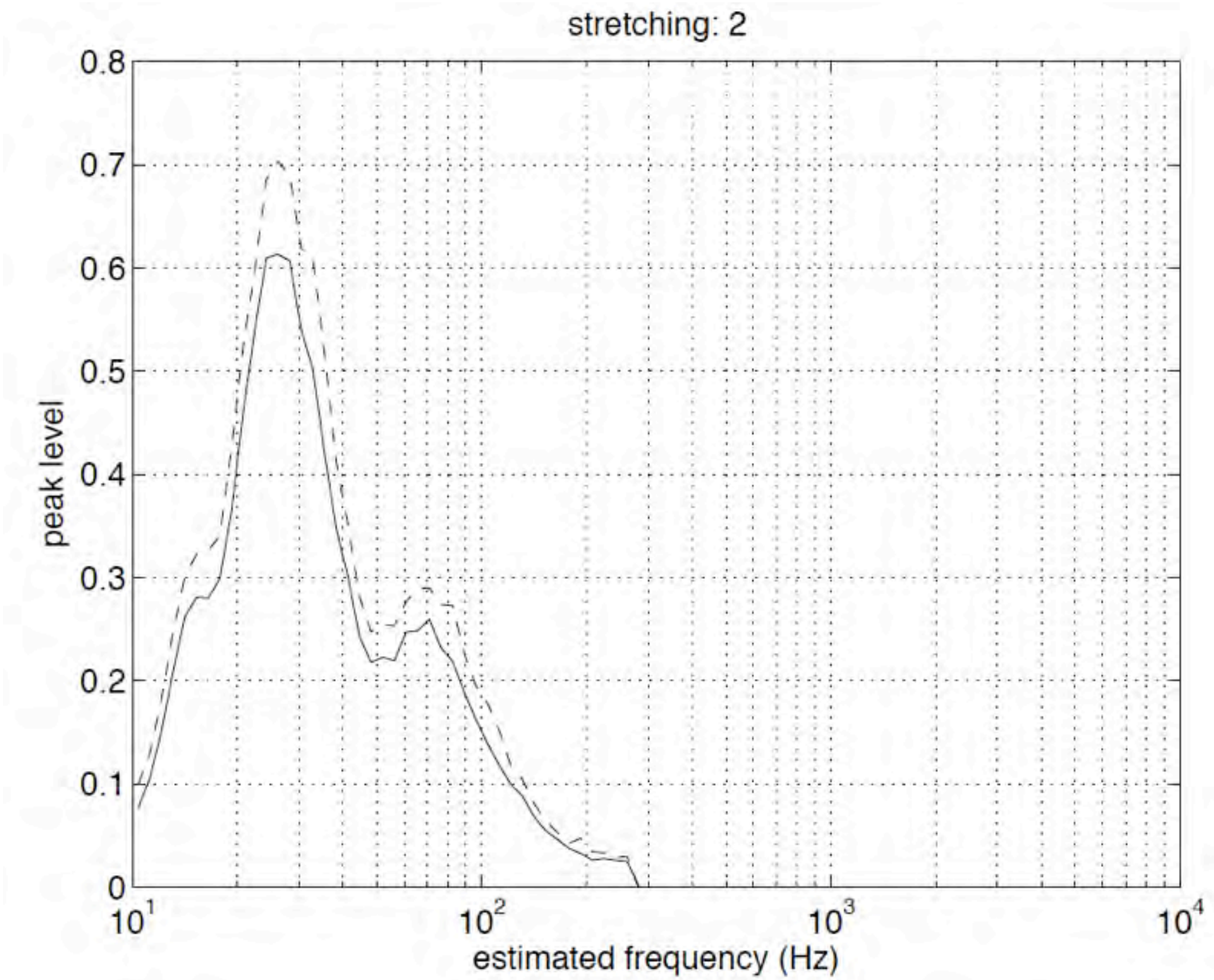
selector of lower frequency region

$$w_{\omega 0,N}(\omega) = c_0 \left(1 + \cos\left(\pi\omega / N\omega_0\right)\right)$$



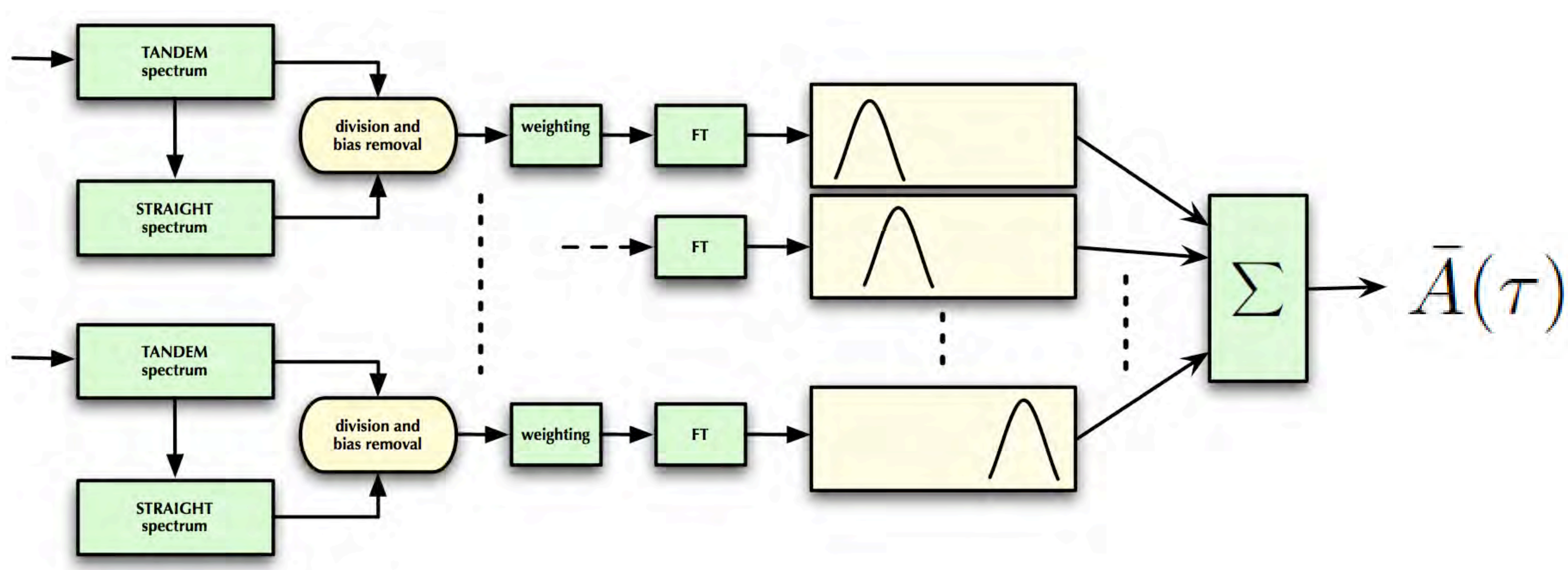
F0 tuned F0 detector

response to random inputs



Group of detectors

combination of detectors to cover wider region



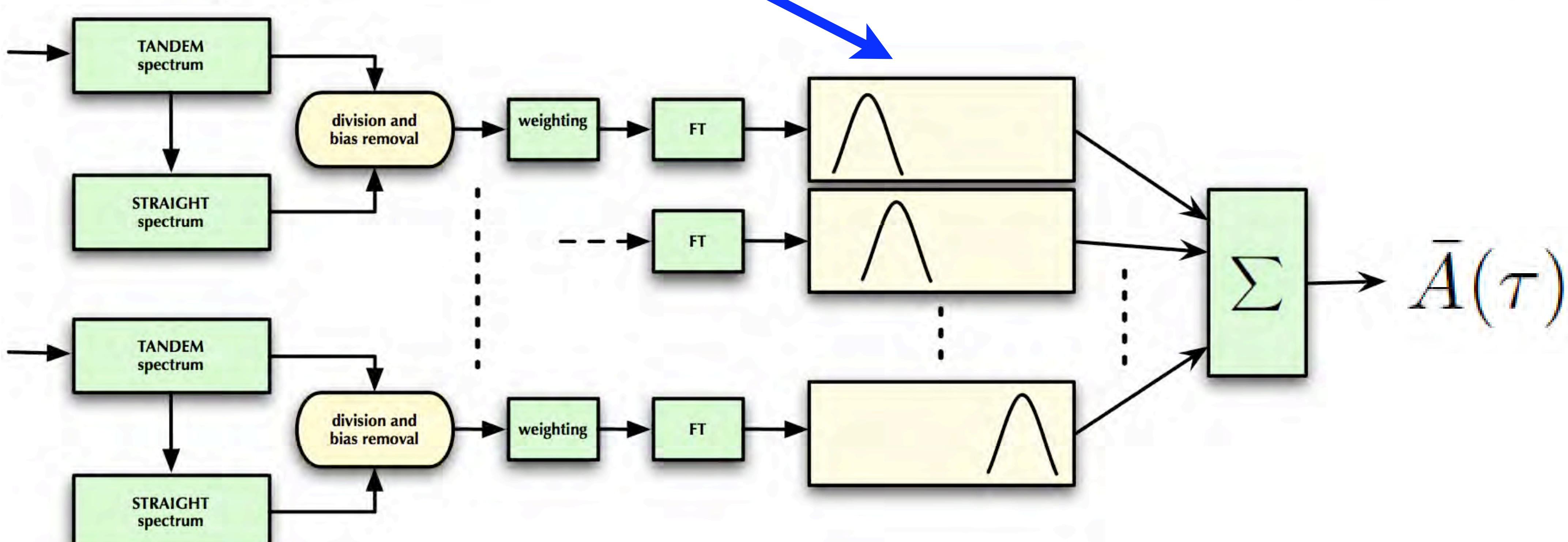
Group of detectors

combination of detectors to cover wider region

selector of a tuned lag region

$$w_{LAG}(\tau; T_0) = 0.5 + 0.5\cos\left(\pi \log_2\left(\frac{\tau}{T_0}\right)\right)$$

$$\bar{A}(\tau) = \frac{1}{M}\sum_{k=1}^{M} w_{LAG}(\tau; T_L 2^{\frac{1-k}{L}}) A\left(\tau; T_L 2^{\frac{1-k}{L}}\right)$$



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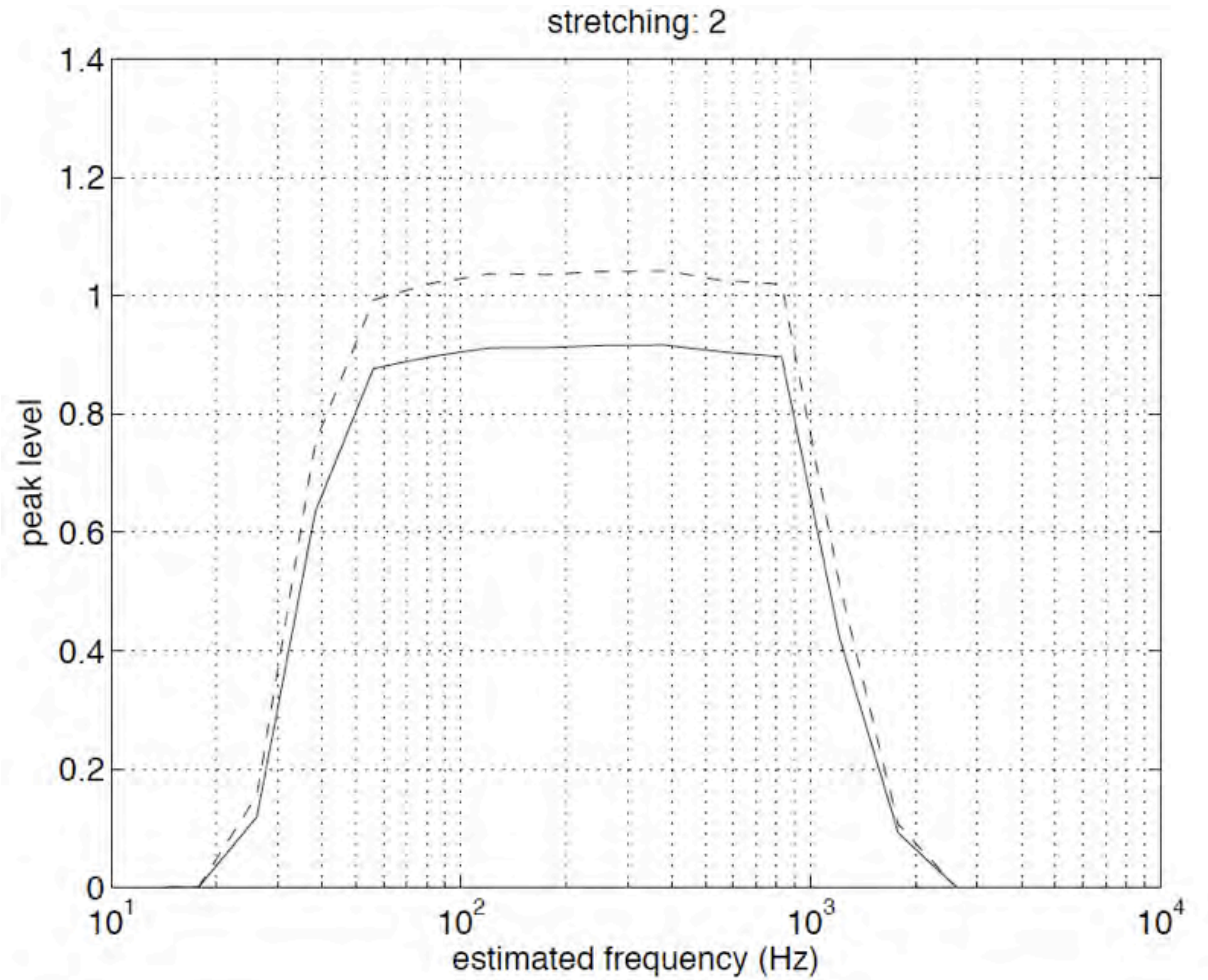

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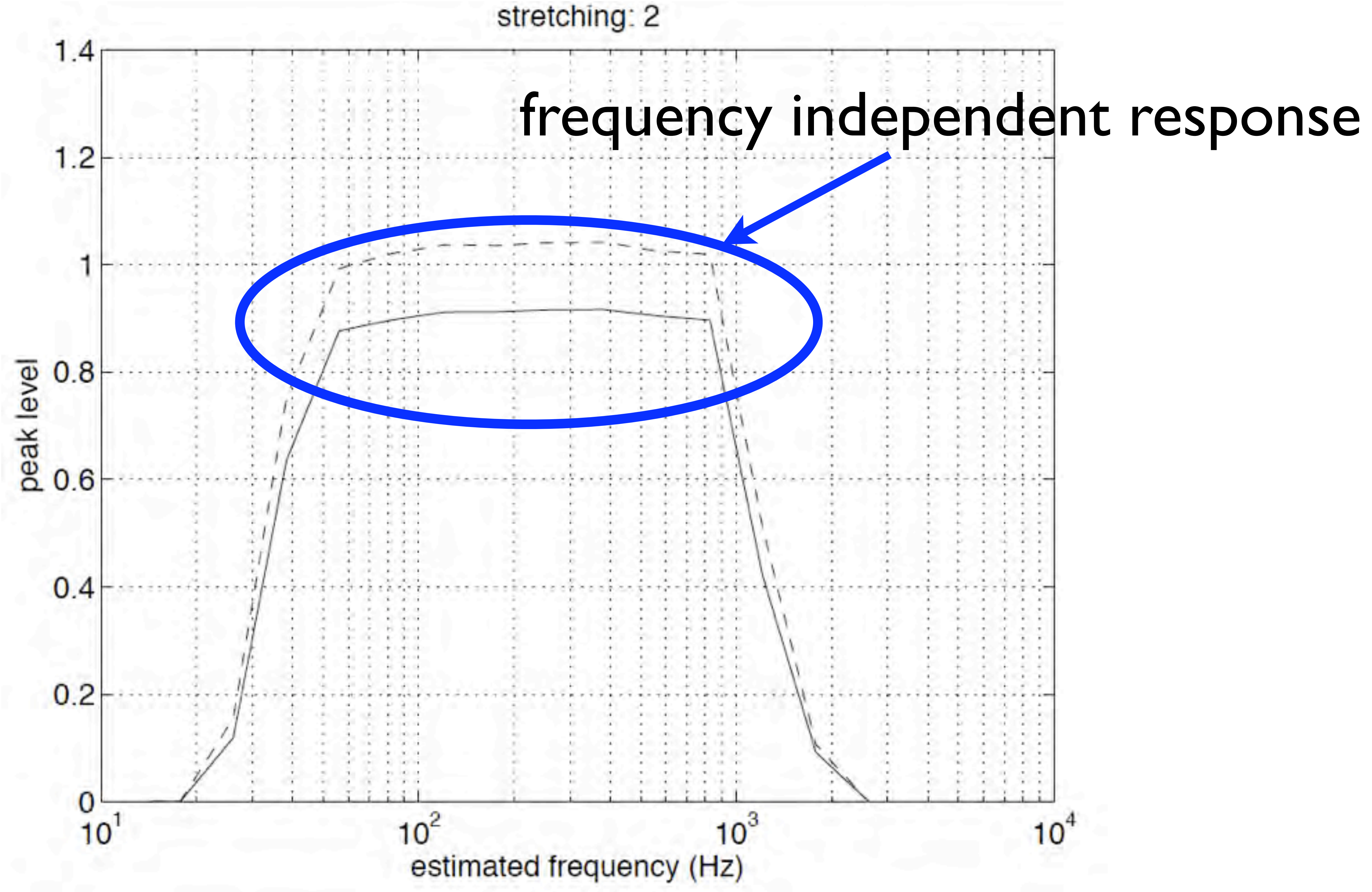
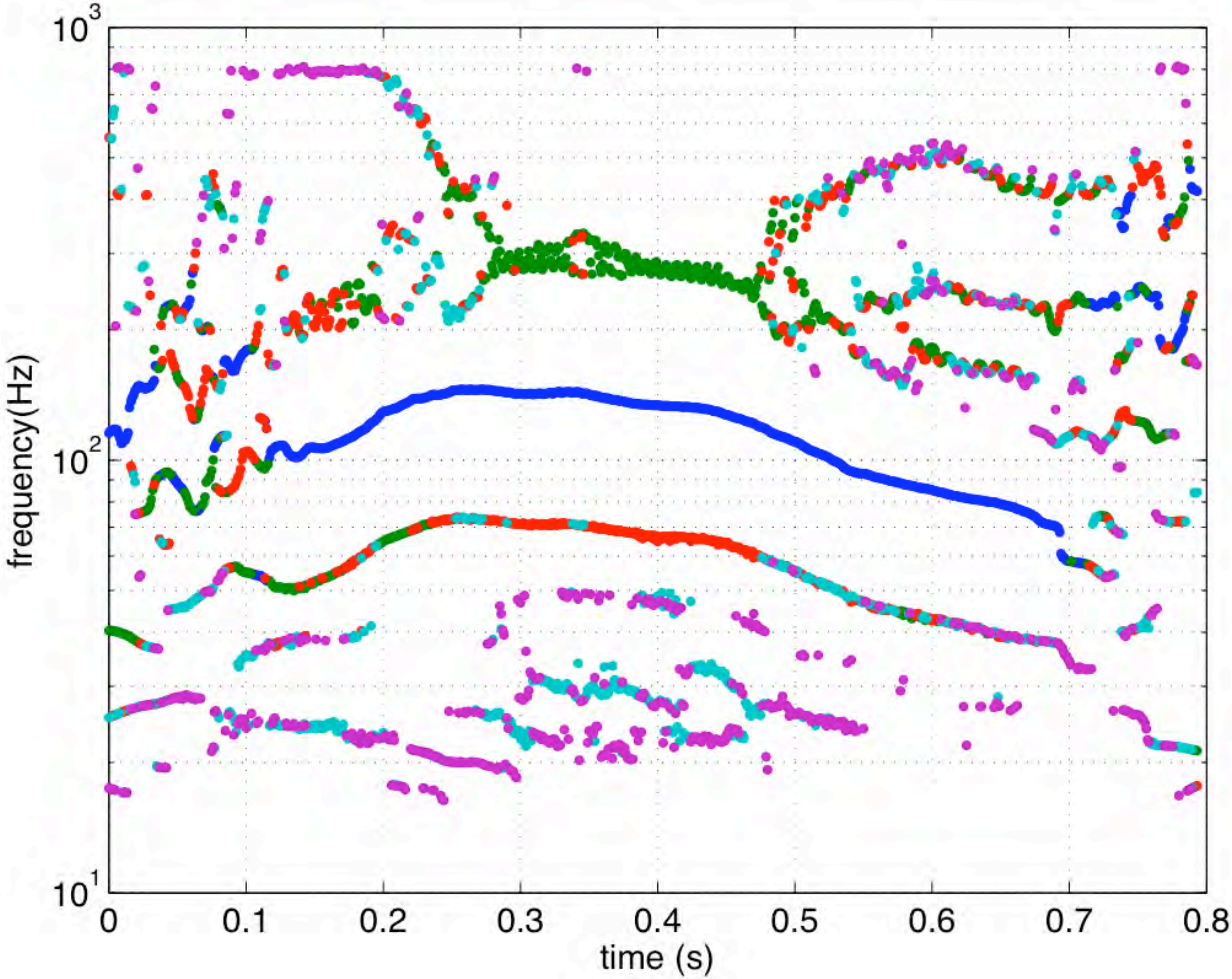
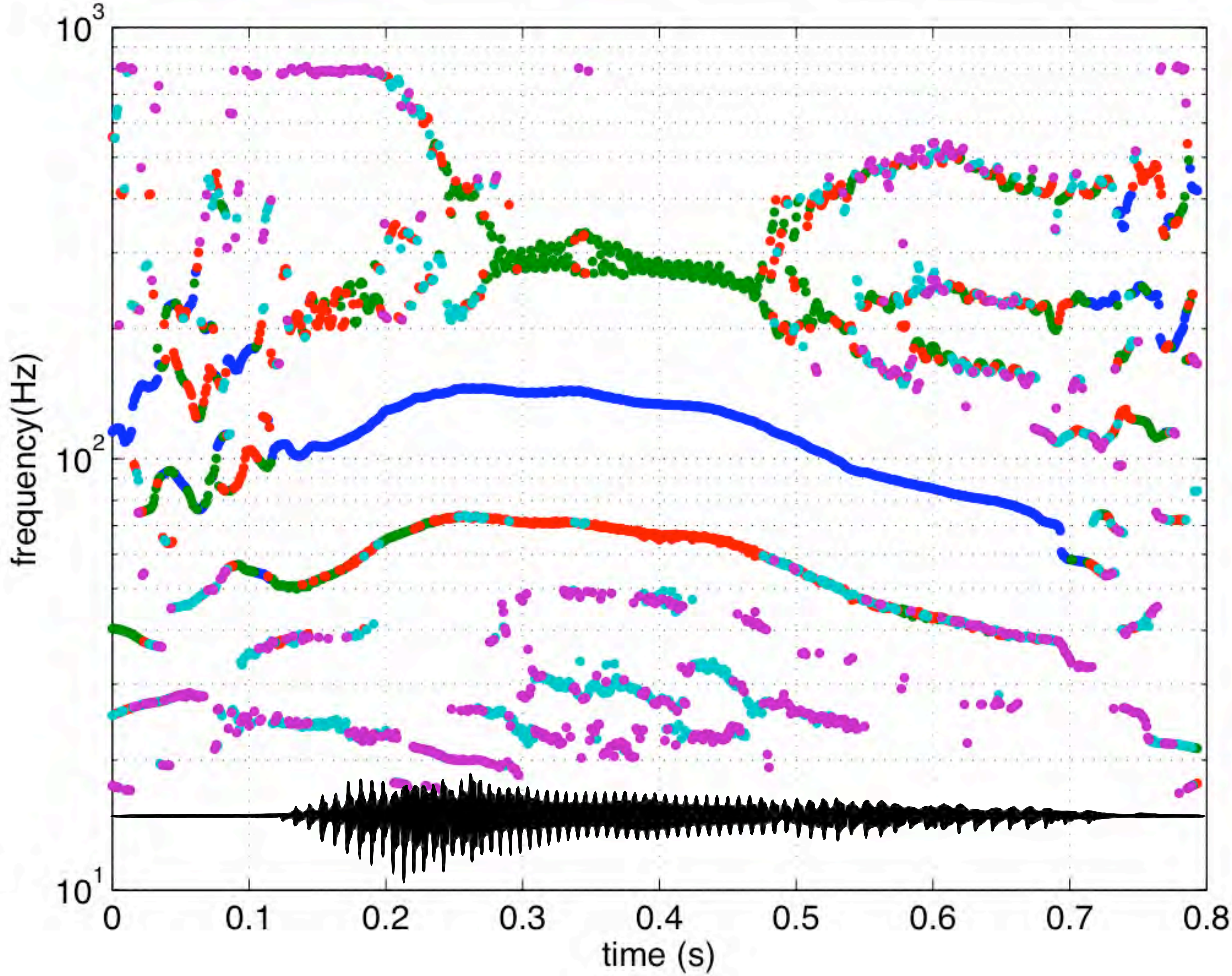


Example

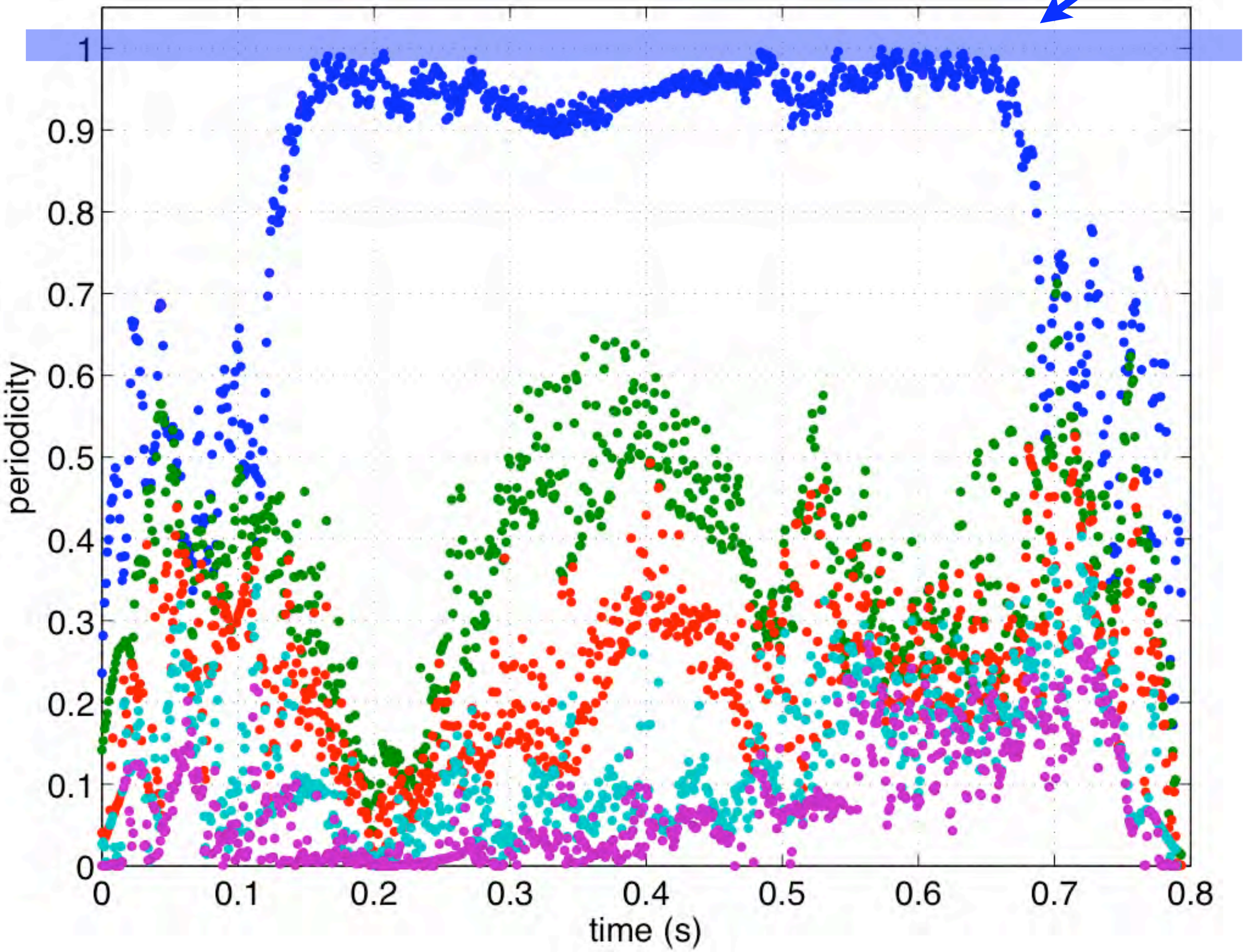


Example

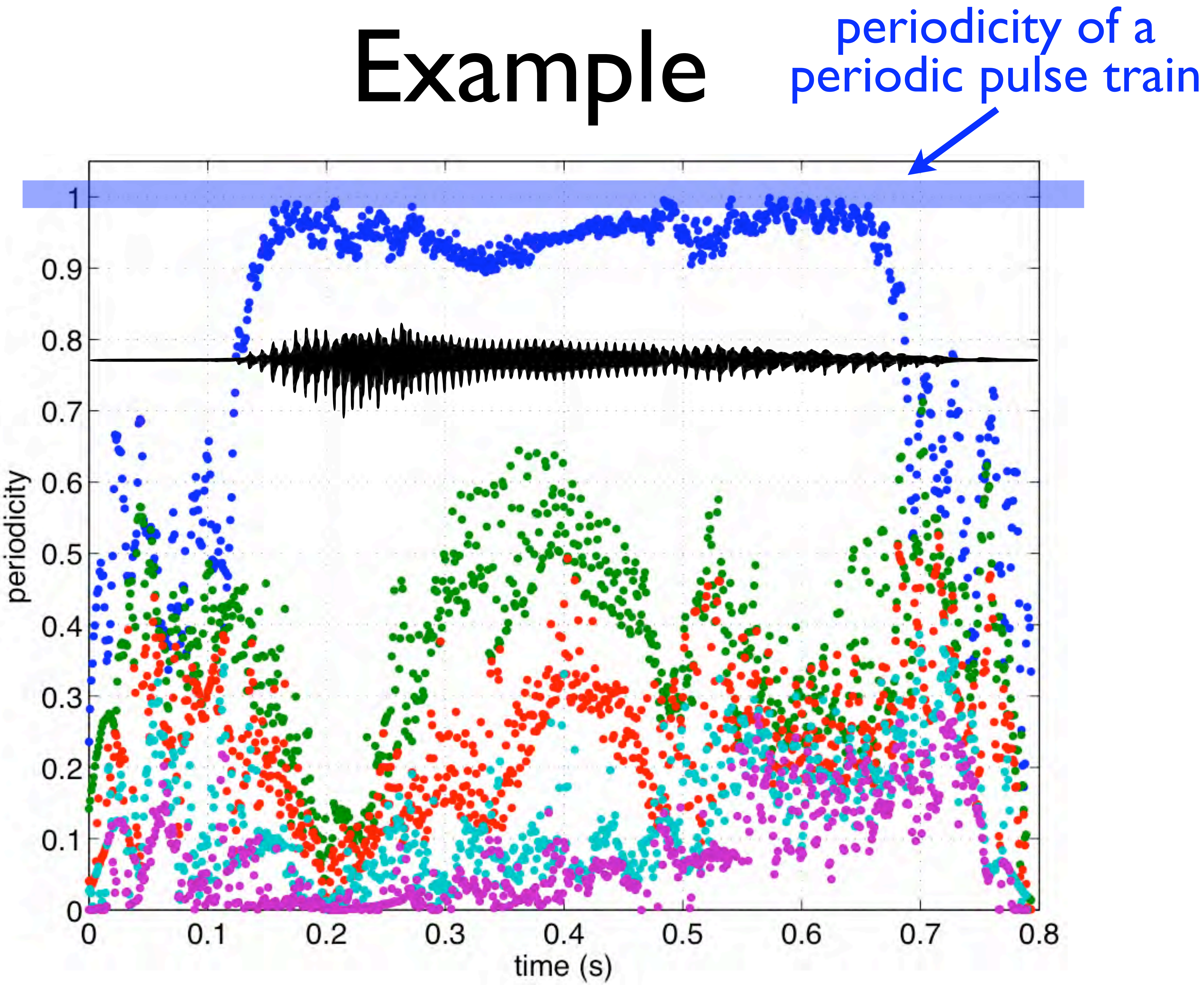


Example

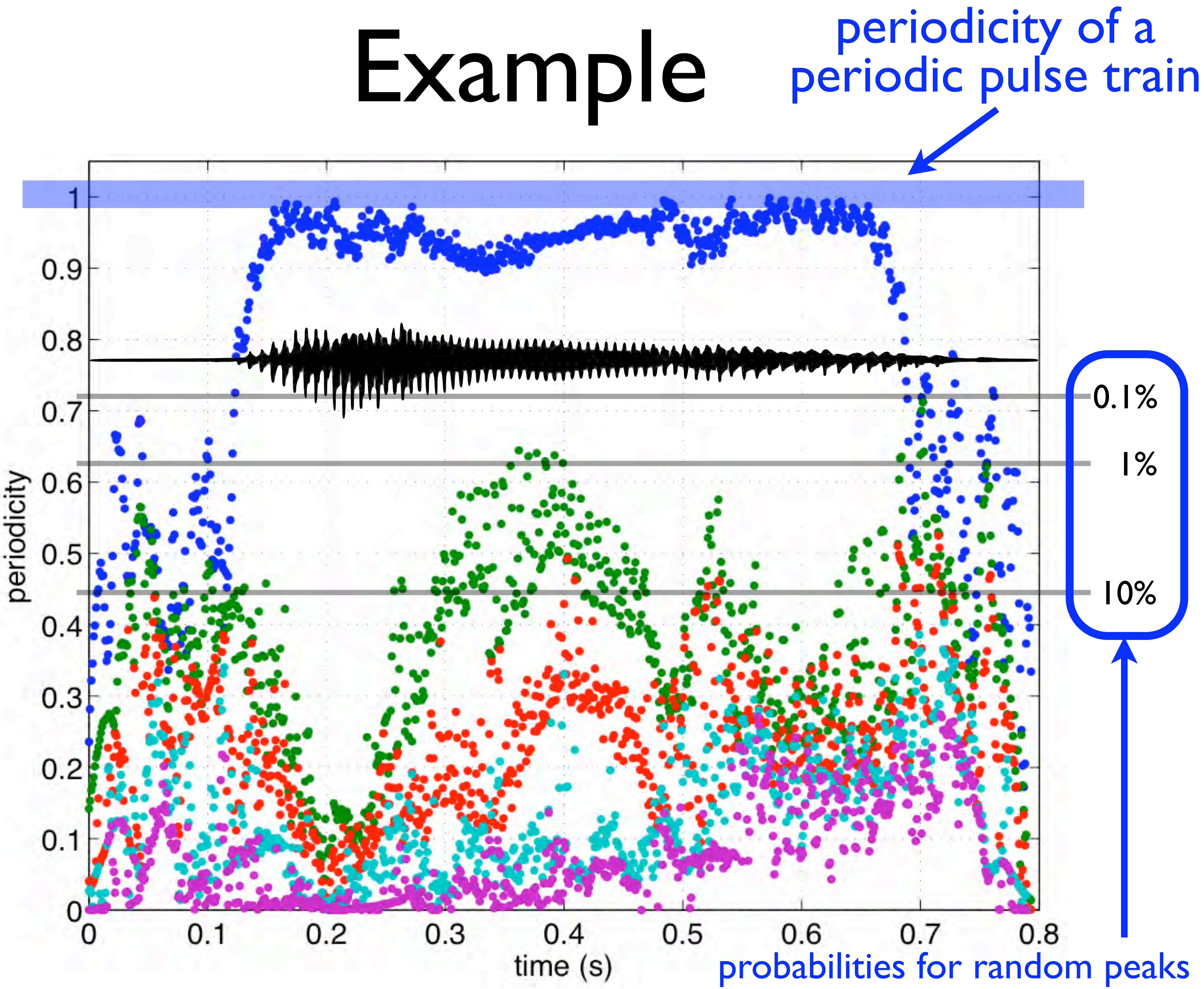
periodicity of a
periodic pulse train



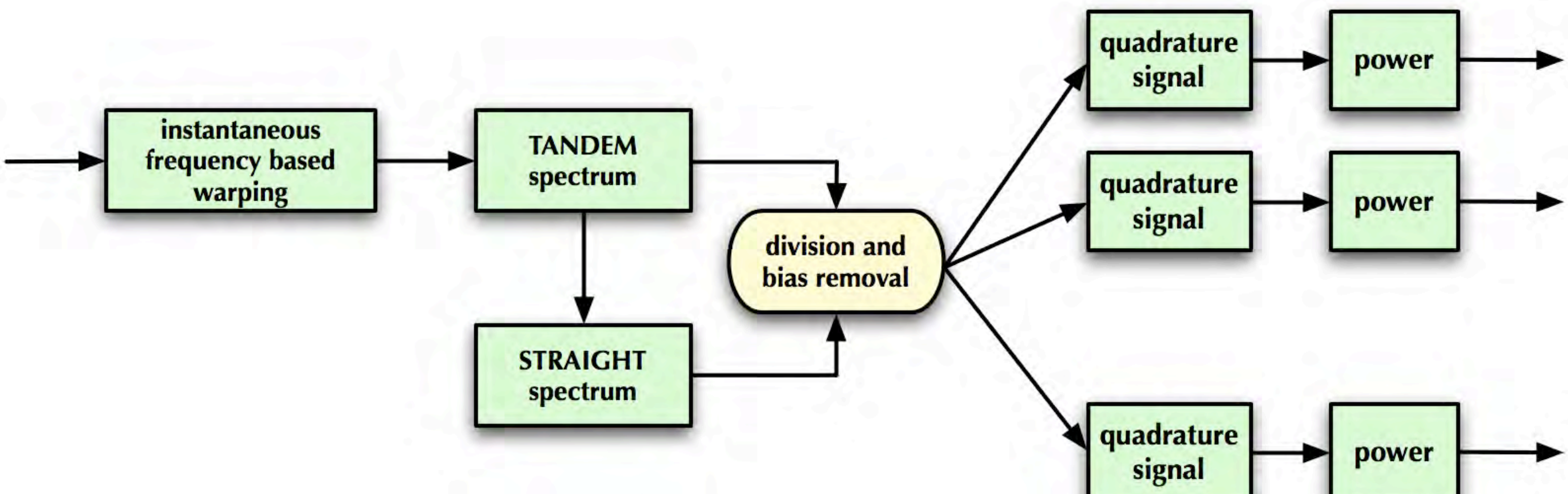
Example


periodicity of a periodic pulse train
periodicity
time (s)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Example


periodicity of a
periodic pulse train
0.1%
1%
10%
probabilities for random peaks
periodicity
time (s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Periodicity spectrogram



Periodicity spectrogram

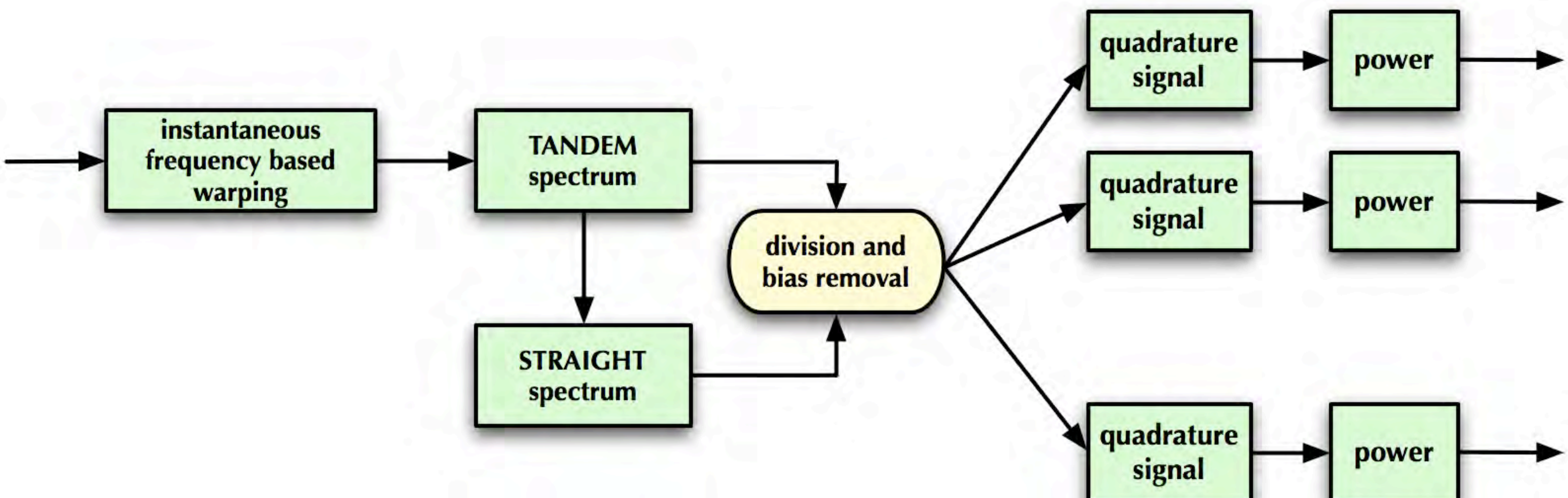
$$Q_C^2(\omega; T_C) = \left| \int_{-\infty}^{\infty} h_N(\lambda; T_C) P_C(\omega - \lambda; T_C) d\lambda \right|^2$$

quadrature signal to select
F0 related variation

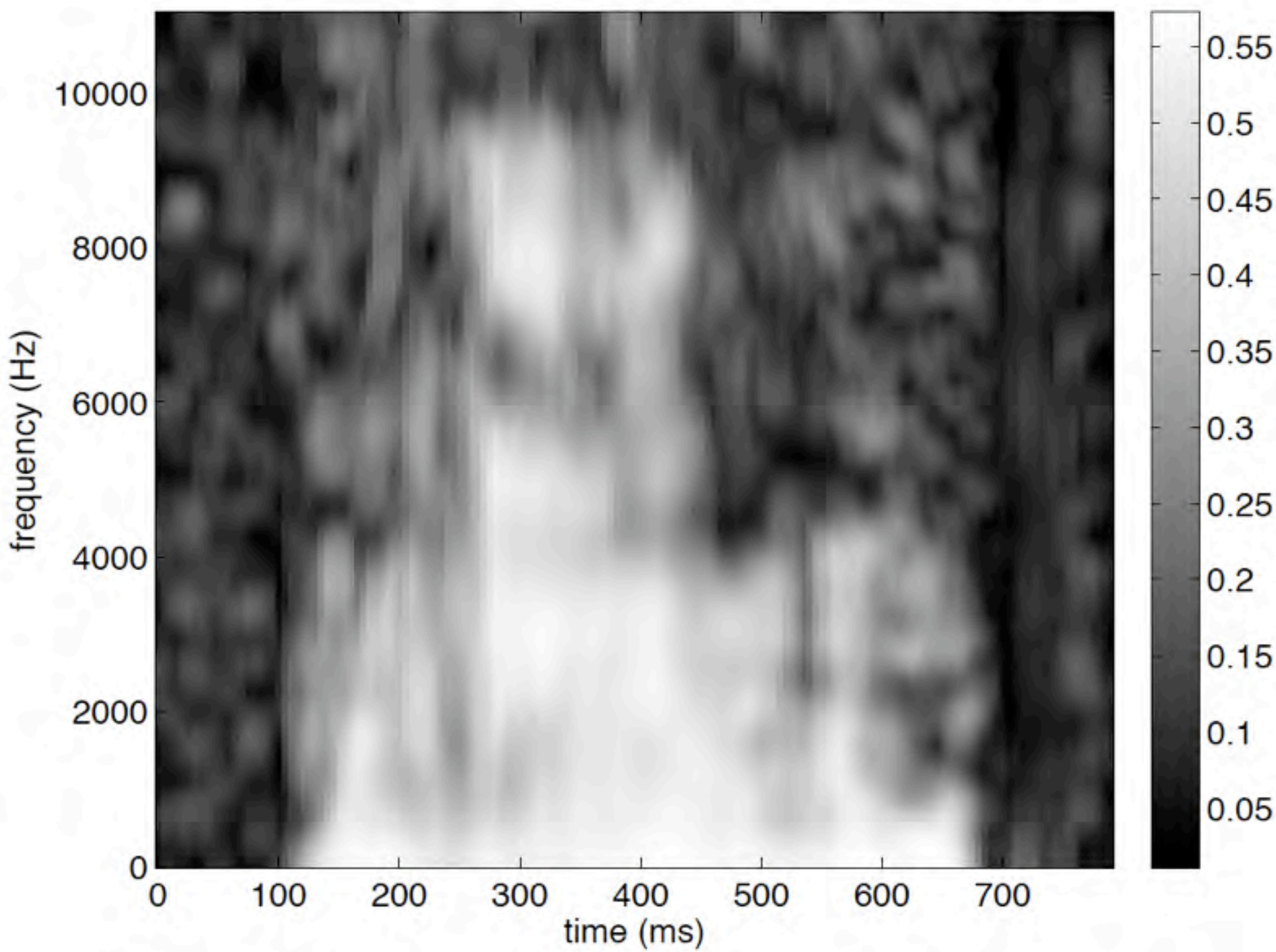
$$h_N(\omega) = w_{\omega 0, N}(\omega) \exp\left(2\pi j \omega / \omega_0\right)$$

a practical implementation
of envelope

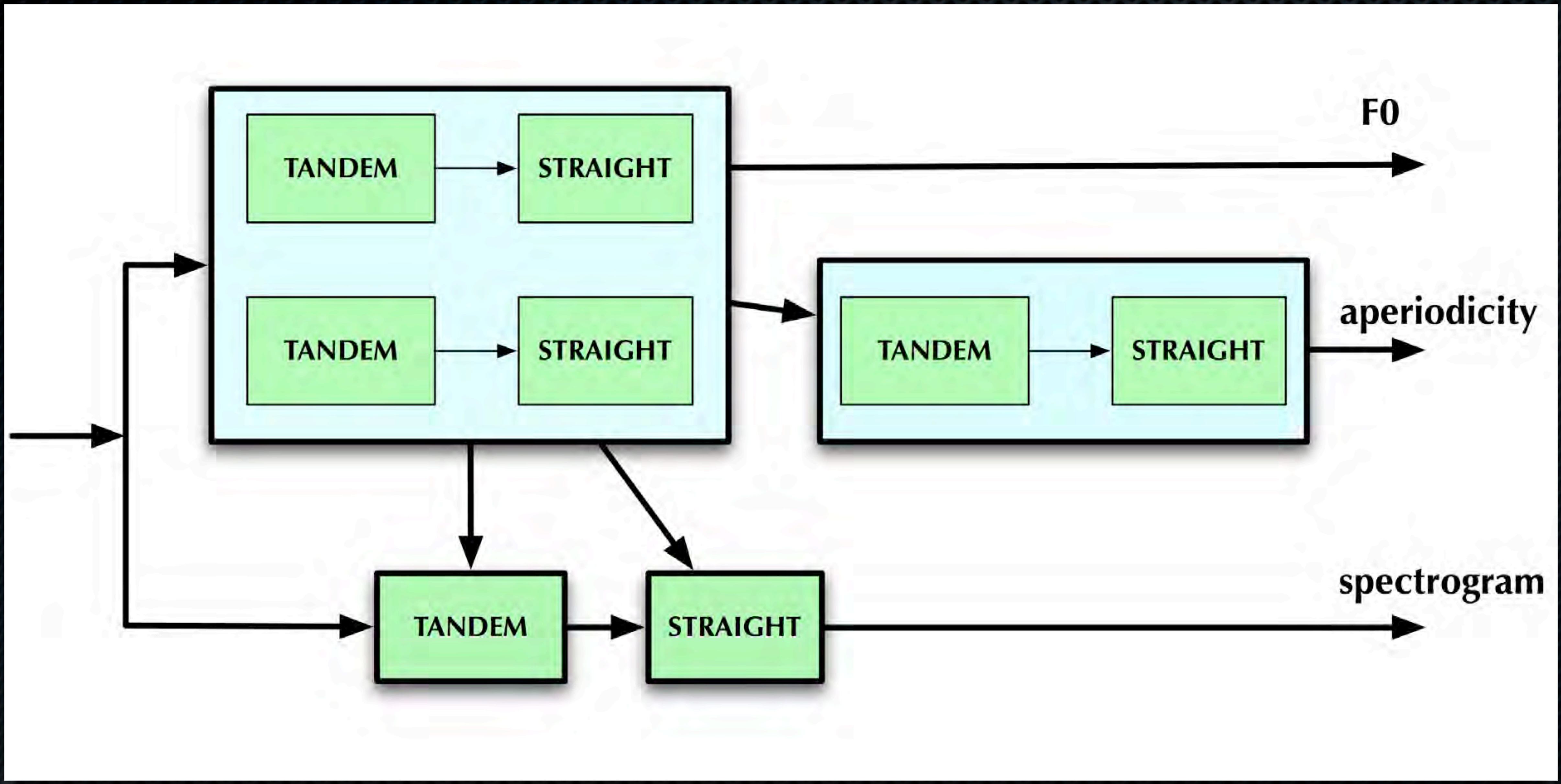
$$w_{\omega_C, N}(\omega) = c_0 \left(1 + \cos\left(\pi \omega / N \omega_C\right)\right)$$



Example

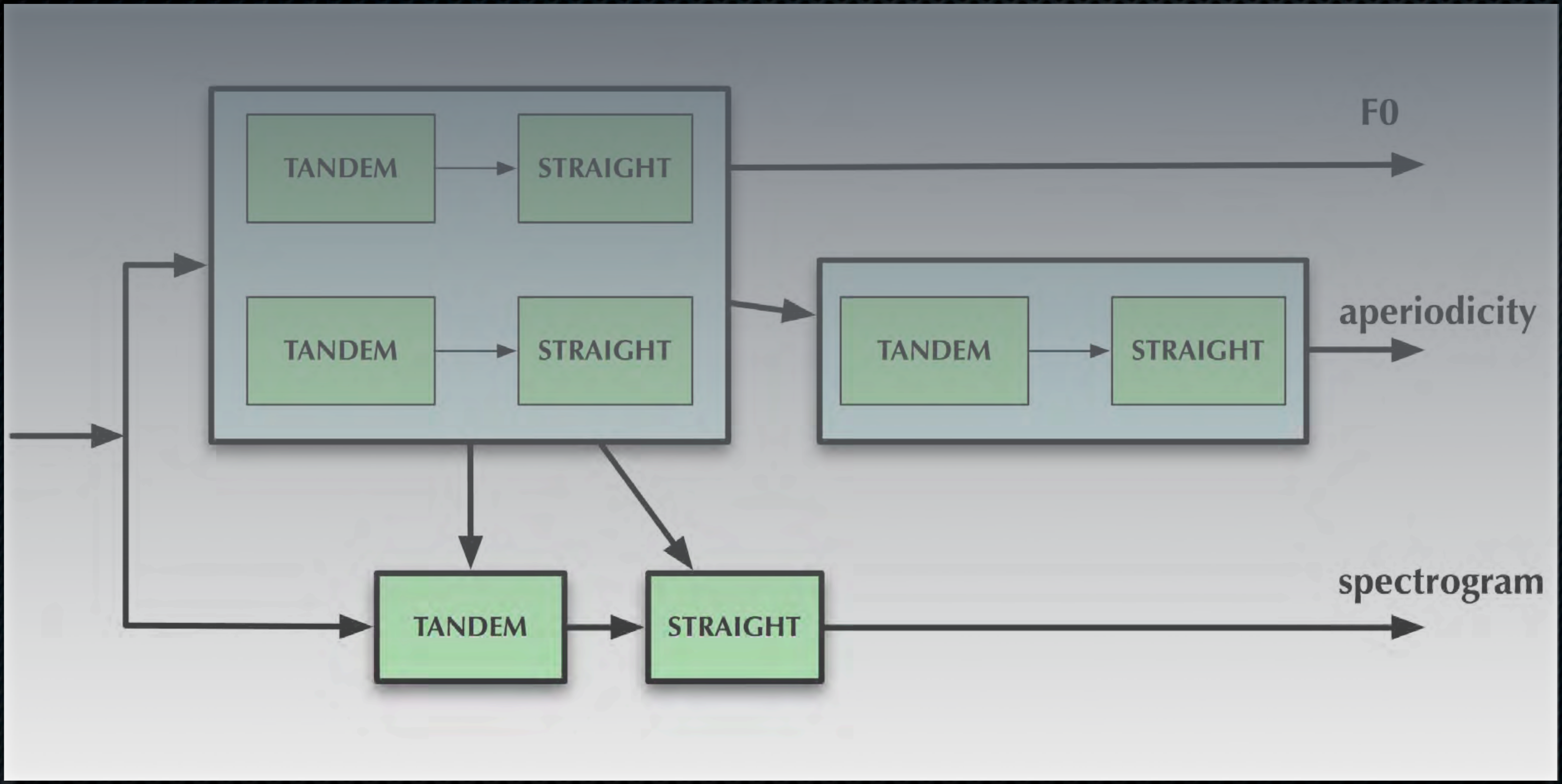


10000
8000
6000
4000
2000
0
frequency (Hz)
0
100
200
300
400
500
600
700
time (ms)
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05



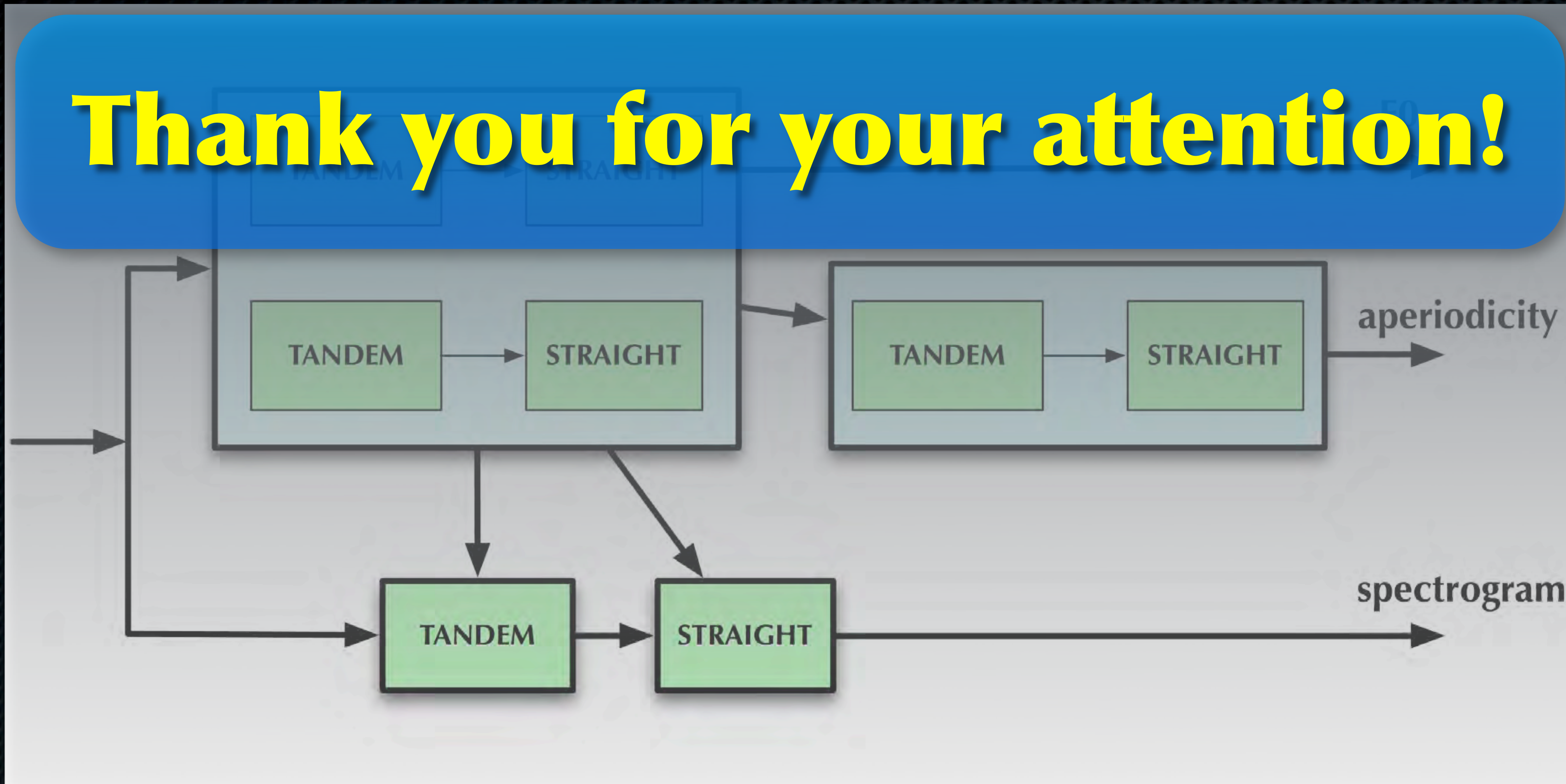
Concluding remarks

TANDEM-STRAIGHT is theoretically tractable



Concluding remarks

TANDEM-STRAIGHT is theoretically tractable

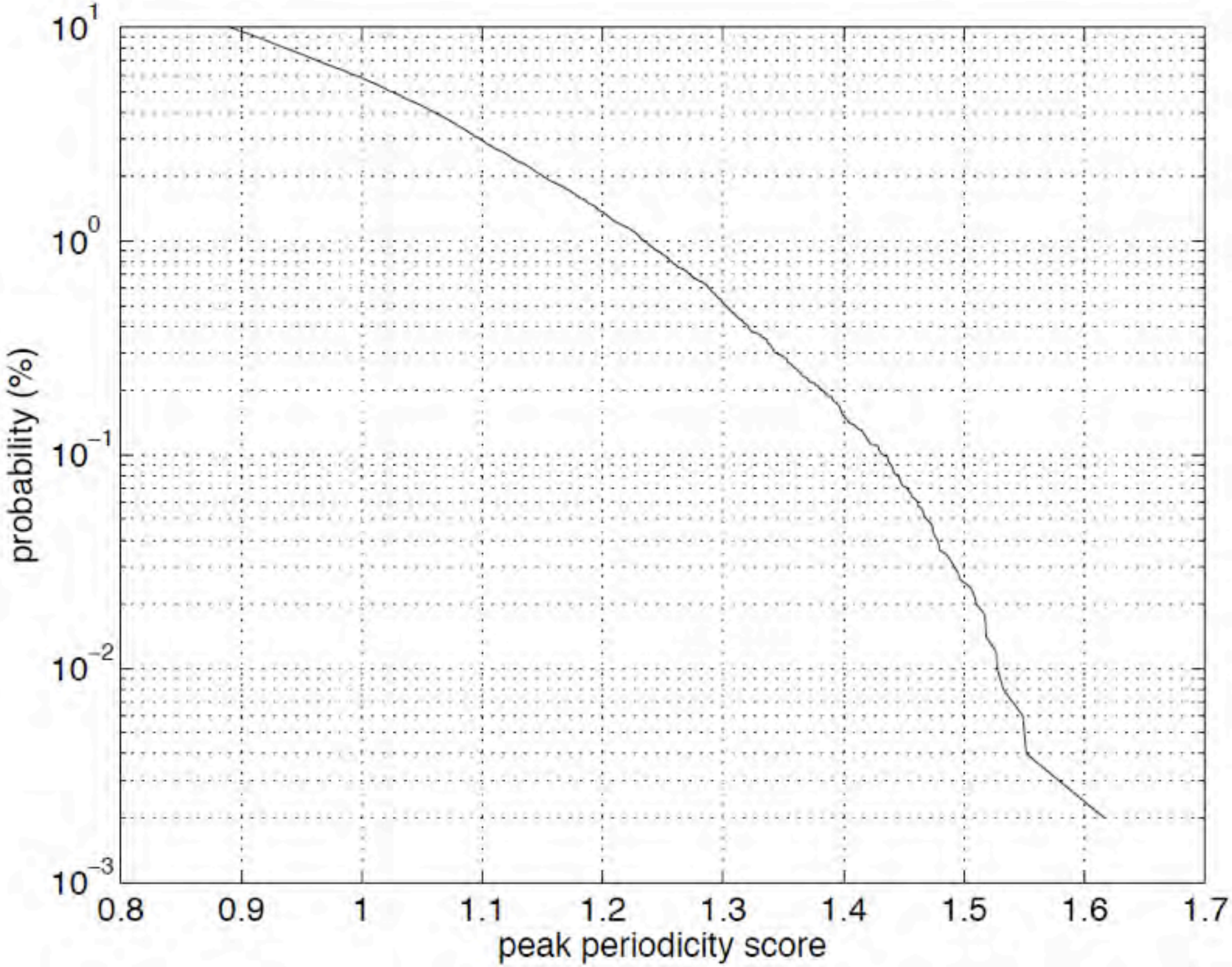


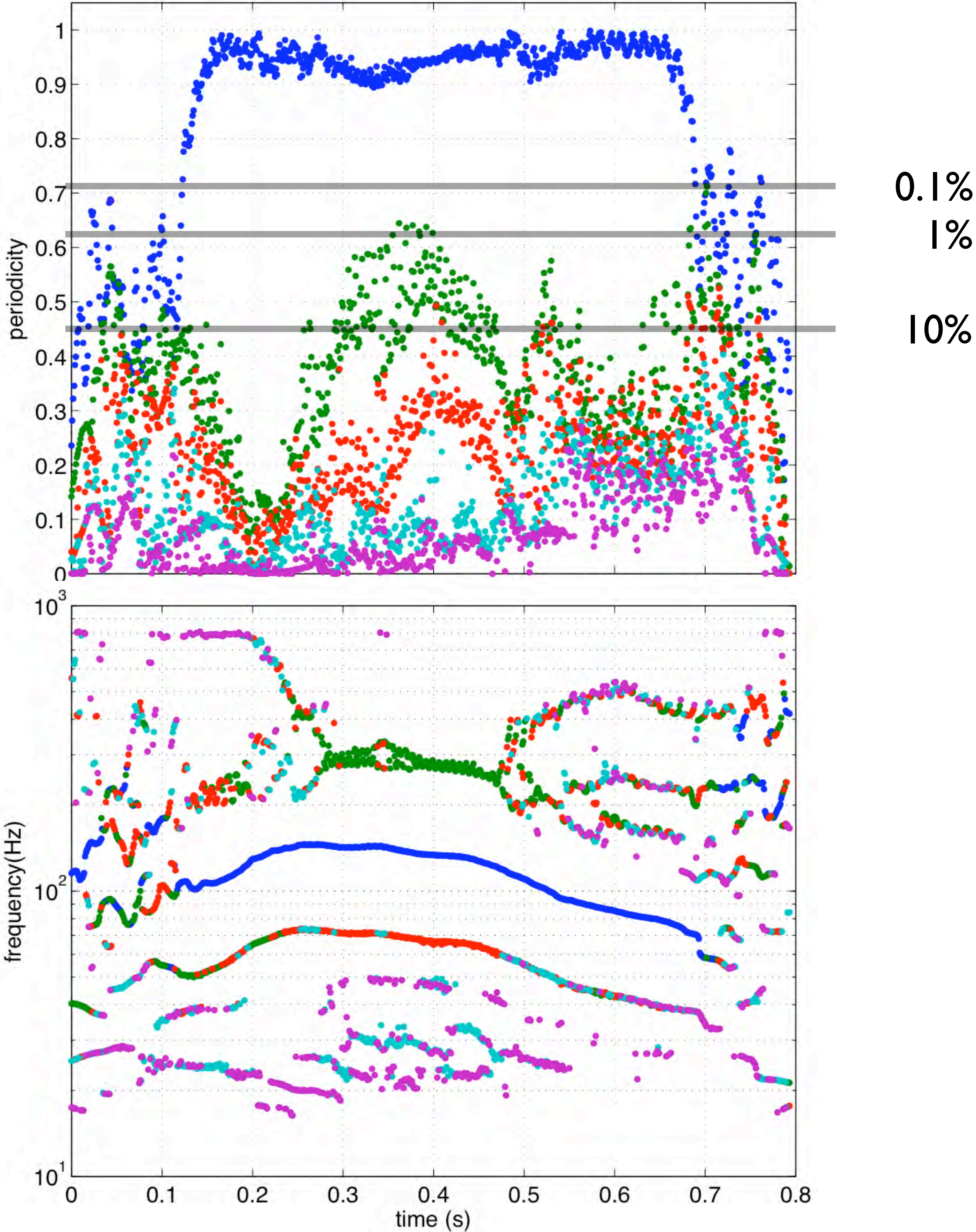
Concluding remarks

TANDEM-STRAIGHT is theoretically tractable

Appendix

Combined F0 detectors





periodicity
0.1%
1%
10%
frequency(Hz)
time (s)