A fast EEMD algorithm and decomposition quality criteria for paleoclimate signal analysis

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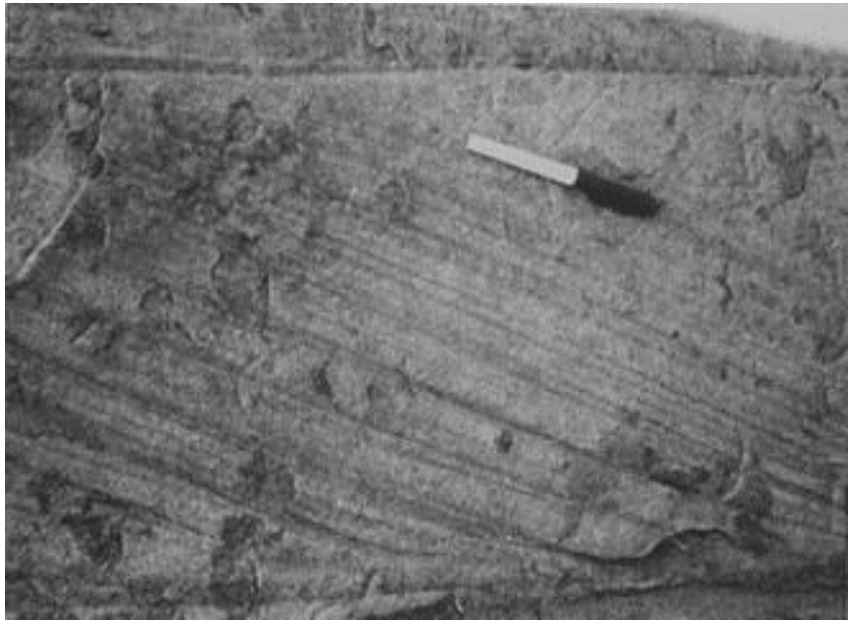
Context

Introduction

- **Cyclostratigraphy**: the study of sedimentary cycles
- **Astrochronology**: the use of sedimentary cycles for duration estimation by the identification of Milankovitch cycles



Mazumder & Arima, 2005

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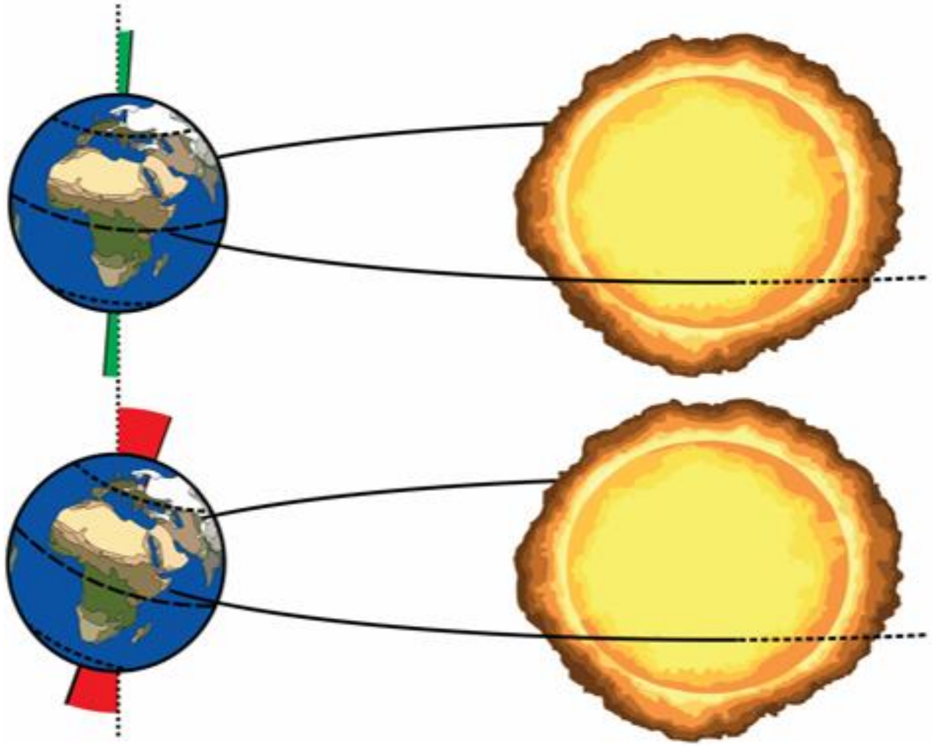
Astronomical cycles

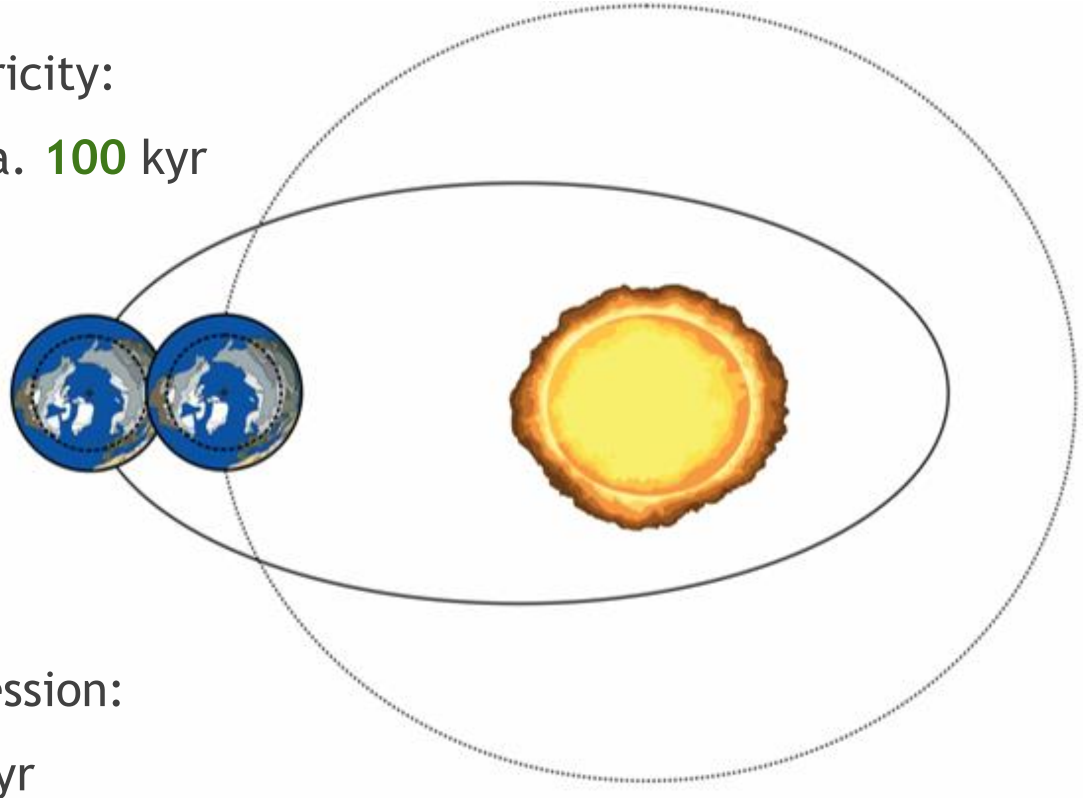
- Obliquity

Ca. 40 kyr



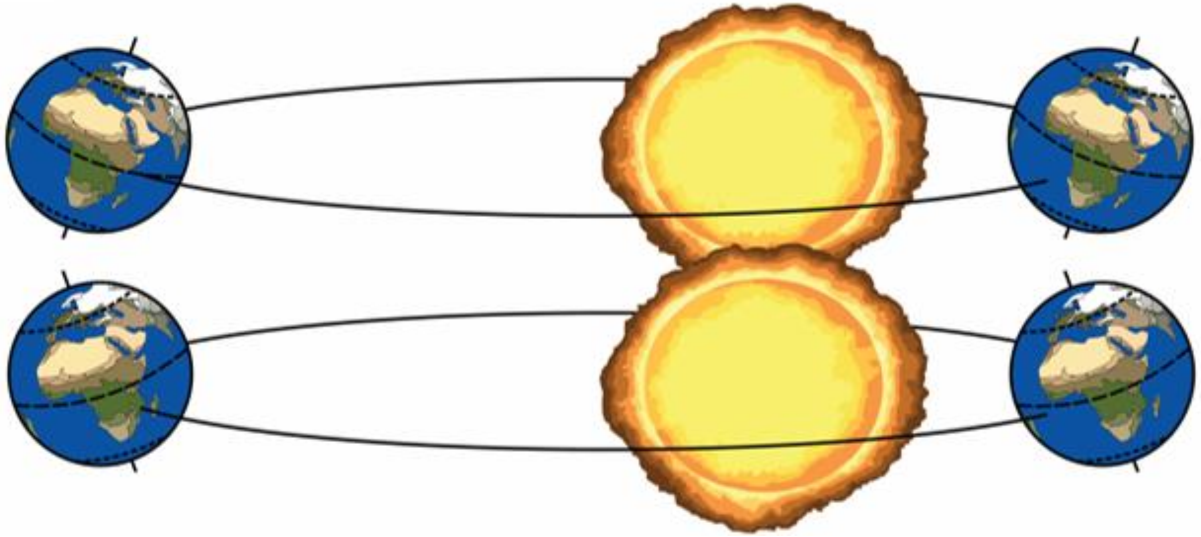
- Eccentricity:

405 and ca. 100 kyr



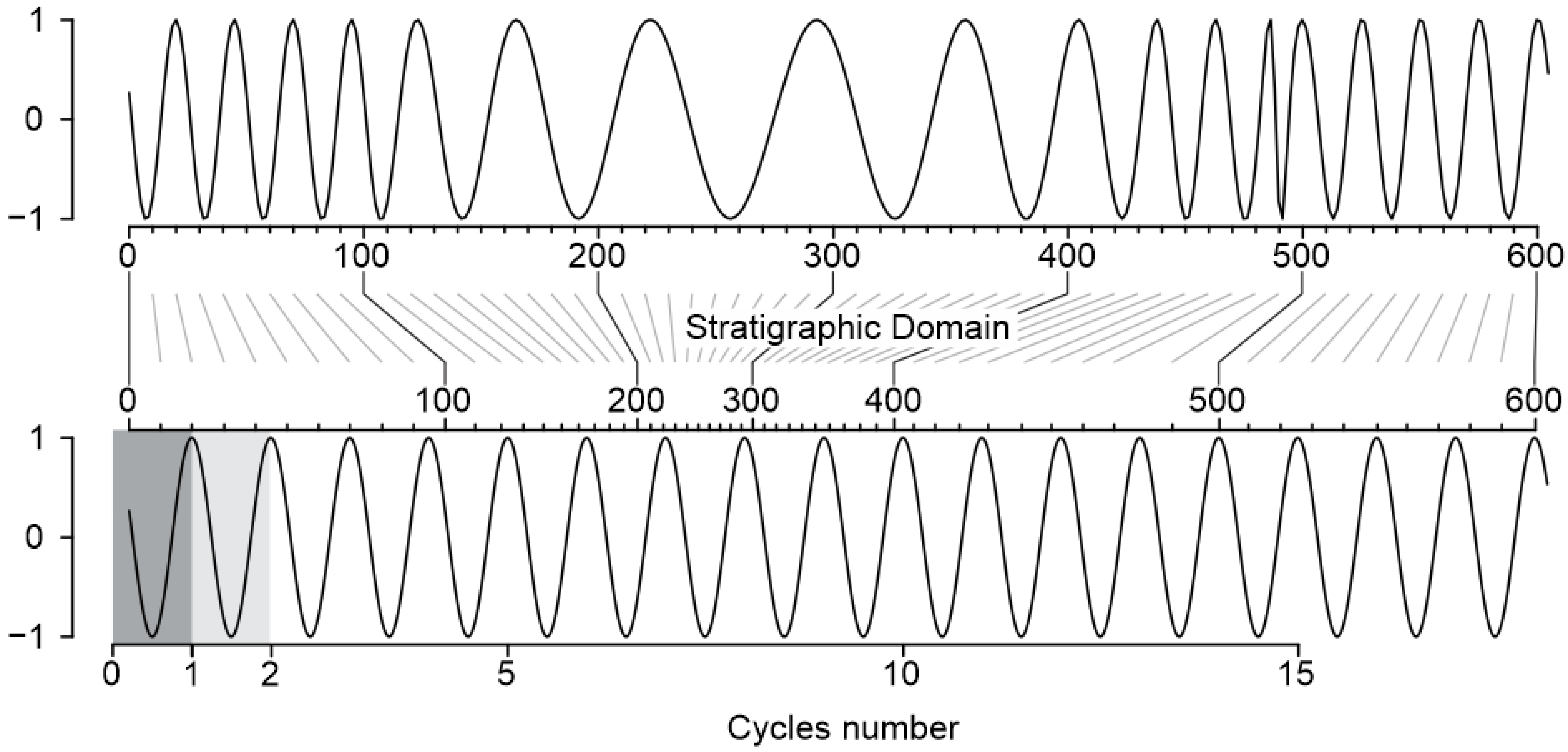
- Precession:

Ca. 20 kyr



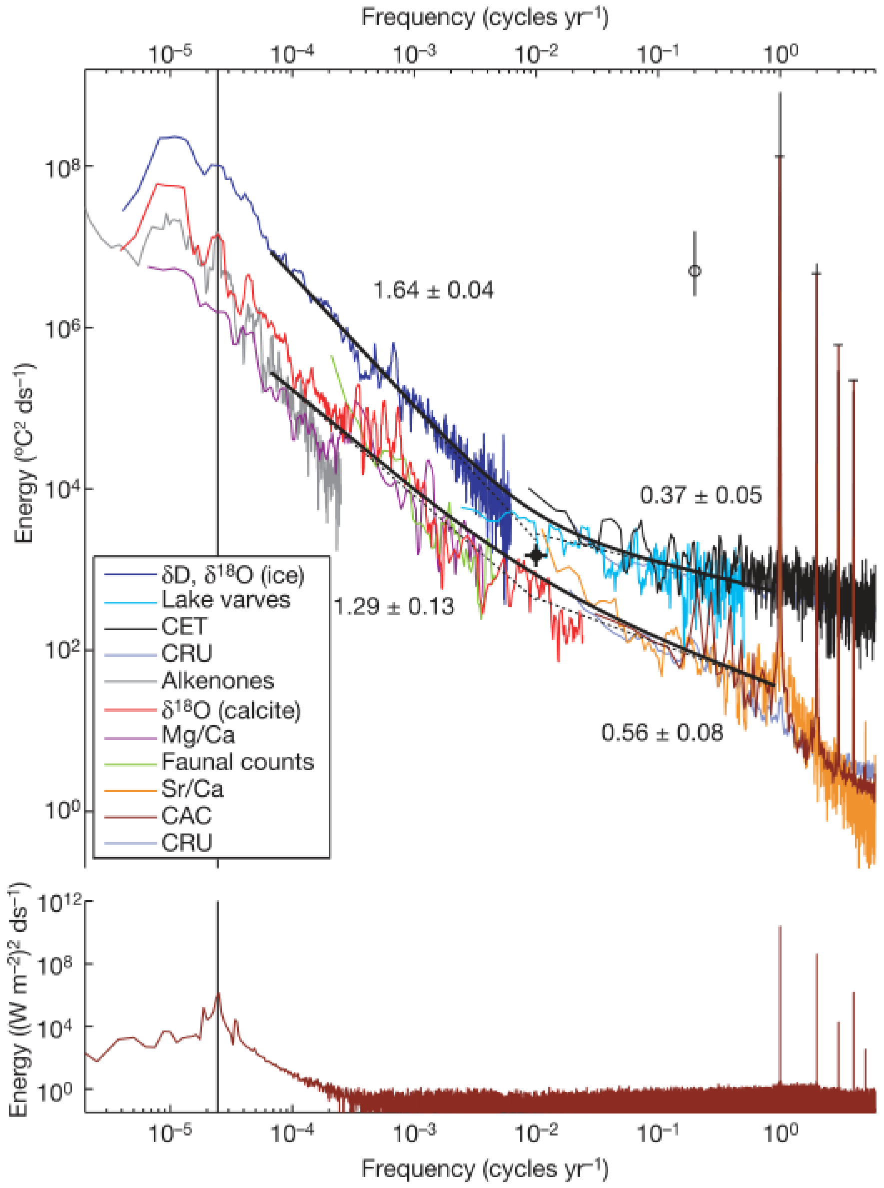
What are the problems to identify astronomical cycles ?

Sedimentation rate changes
Or time-distortion



Heterogeneous processes
Or reaction-diffusion systems

Westphal et al., 2015



Patch-work spectral estimate using instrumental and proxy records of surface temperature variability, and insolation at 65° N.

Huybers & Curry, 2006

Red and Pink noise

Or climatic continuum variability

- Climate records are typically affected by low-frequency noise processes

Dissipative oscillators

- El Niño-Southern Oscillation (ENSO)
- Millennial oscillations of the ocean circulation
- …

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Dissipative oscillators

- El Niño-Southern Oscillation (ENSO)
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- …

- Finite-memory effect: perturbations make these oscillator irregular (loss of phase)

- Prevalent in the climatic system, can be paced by astronomical cycles, but not necessarily perfectly (insolation cycles can be skipped)

Hiatuses and discontinuities

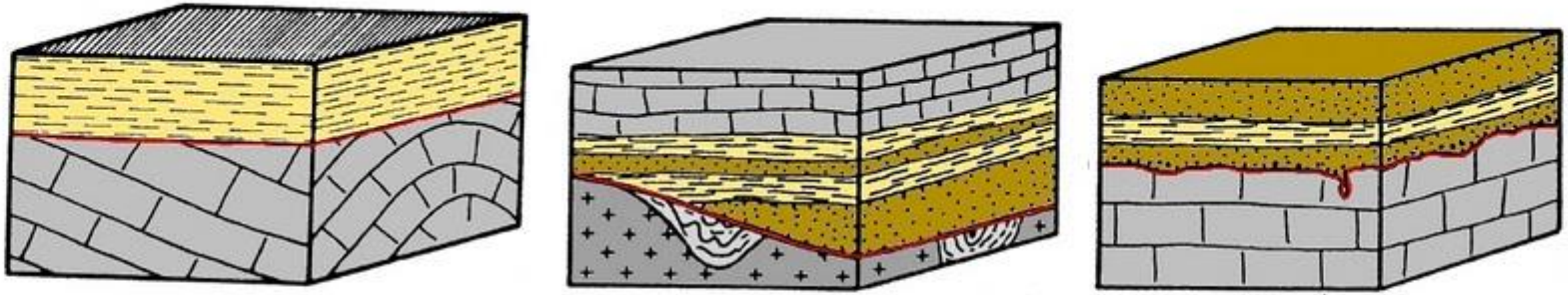
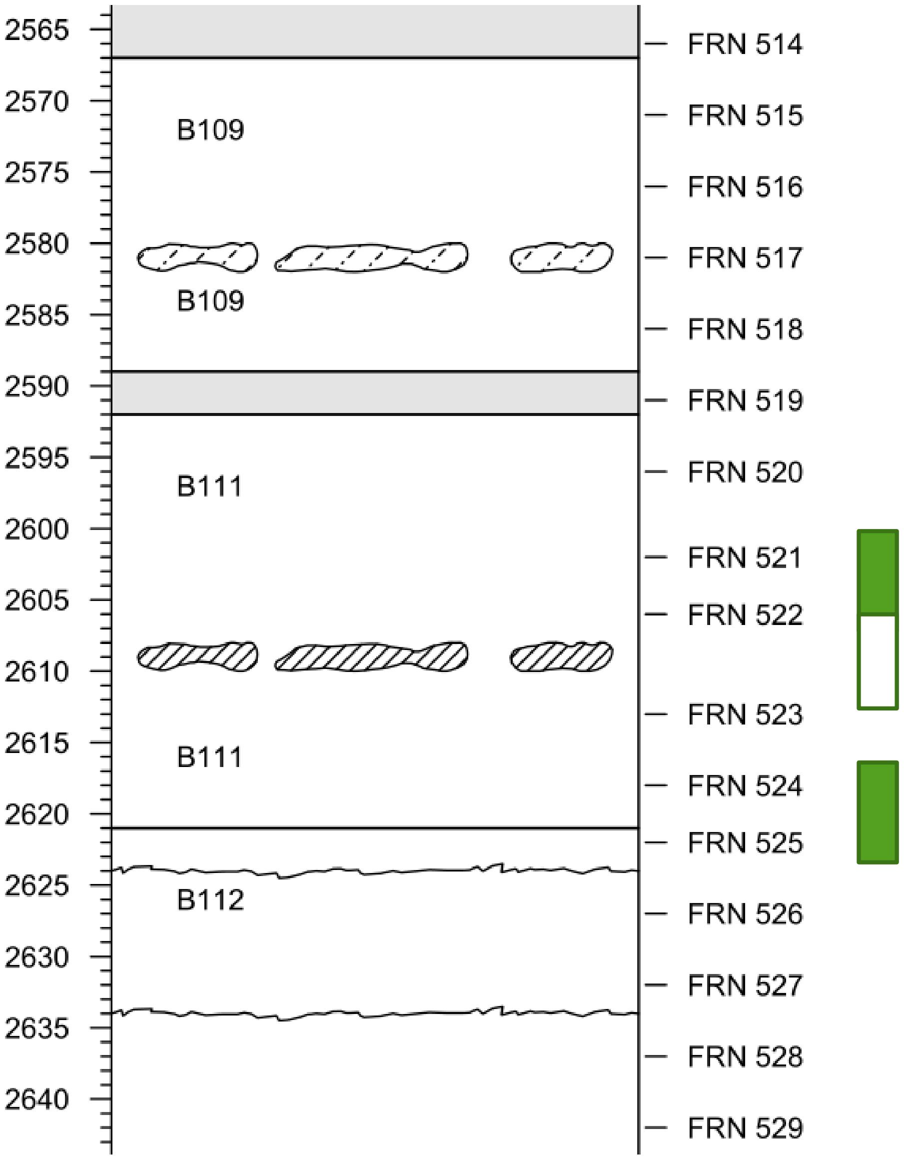


Image credit: Dr Jack Share

Faults

Photo credit: Miguel Vera León

Irregular sampling rate



- Higher sampling rate
- Lower sampling rate
- Higher sampling rate

Reliability of astronomical solutions

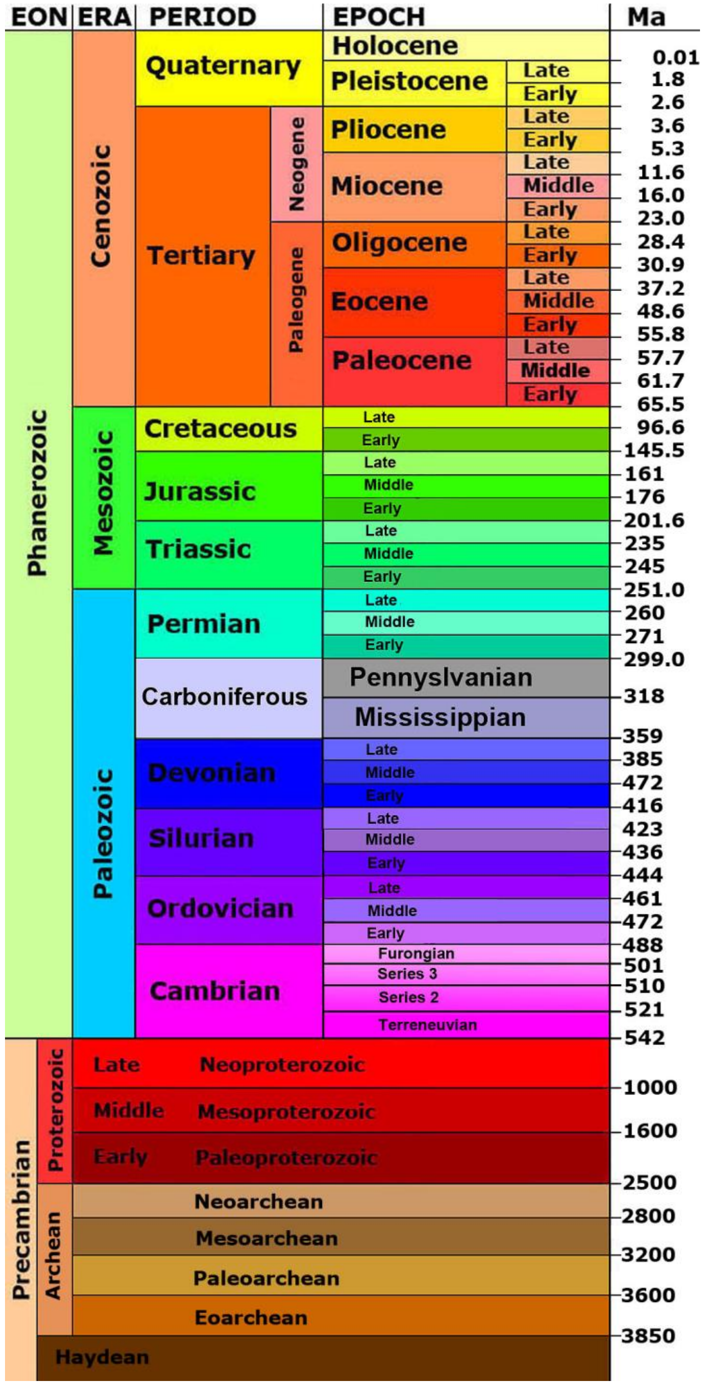


Image credit: gotbooks.miracosta.edu

- Up to **10 Ma**: precession and obliquity solutions (loss due to dissipative effects, tides, etc.)
- Up to **50 Ma**: precise orbits, eccentricity cycles (loss due to deterministic chaotic behaviour)
- Up to **250 Ma**:

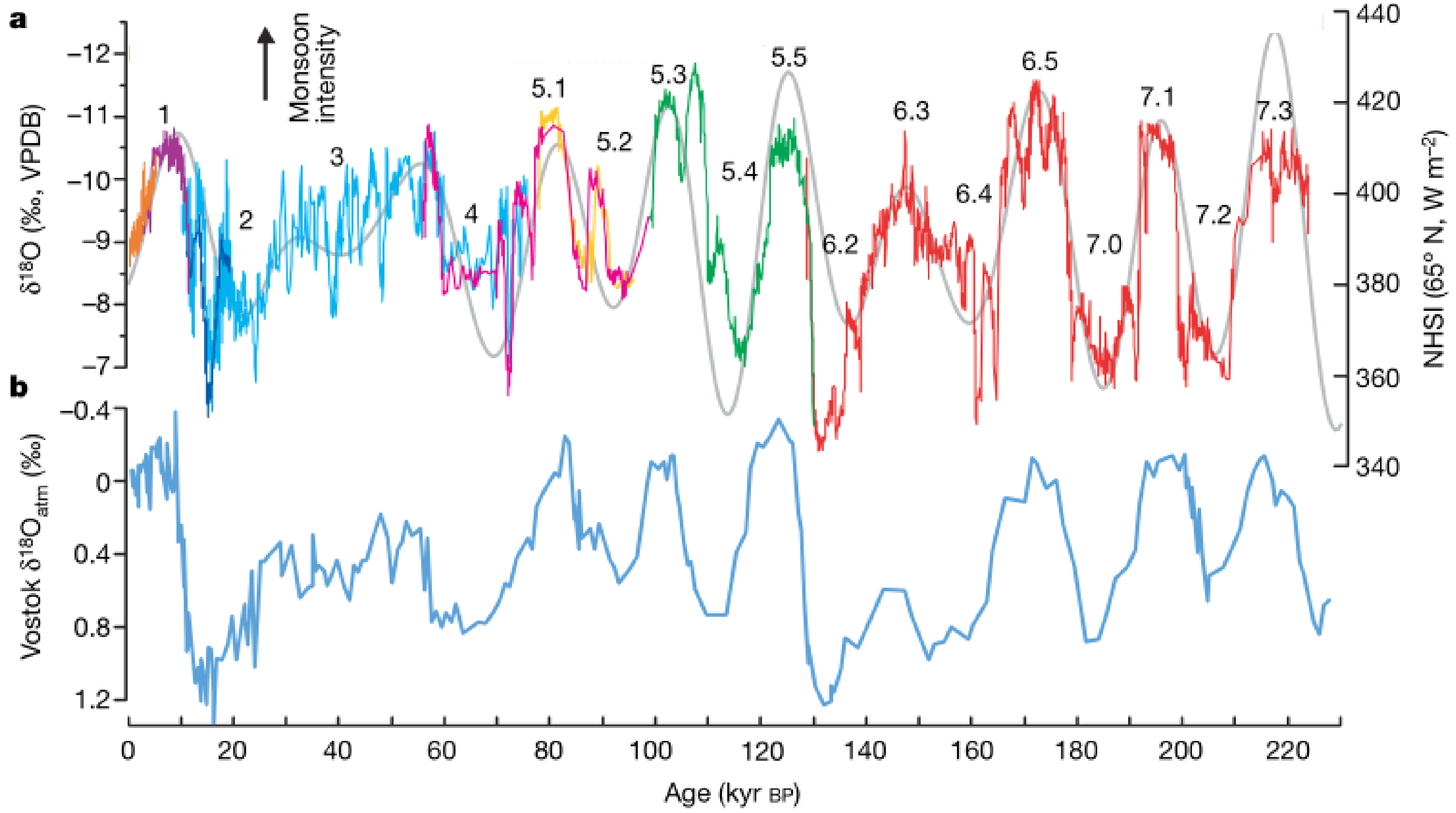
405 kyr eccentricity cycle

173 kyr obliquity amplitude modulation cycle

After 250 Ma: increasingly imprecise estimations on the frequency of cycles

What can we trust to identify astronomical cycles ?

Astronomical solutions (when we have them)

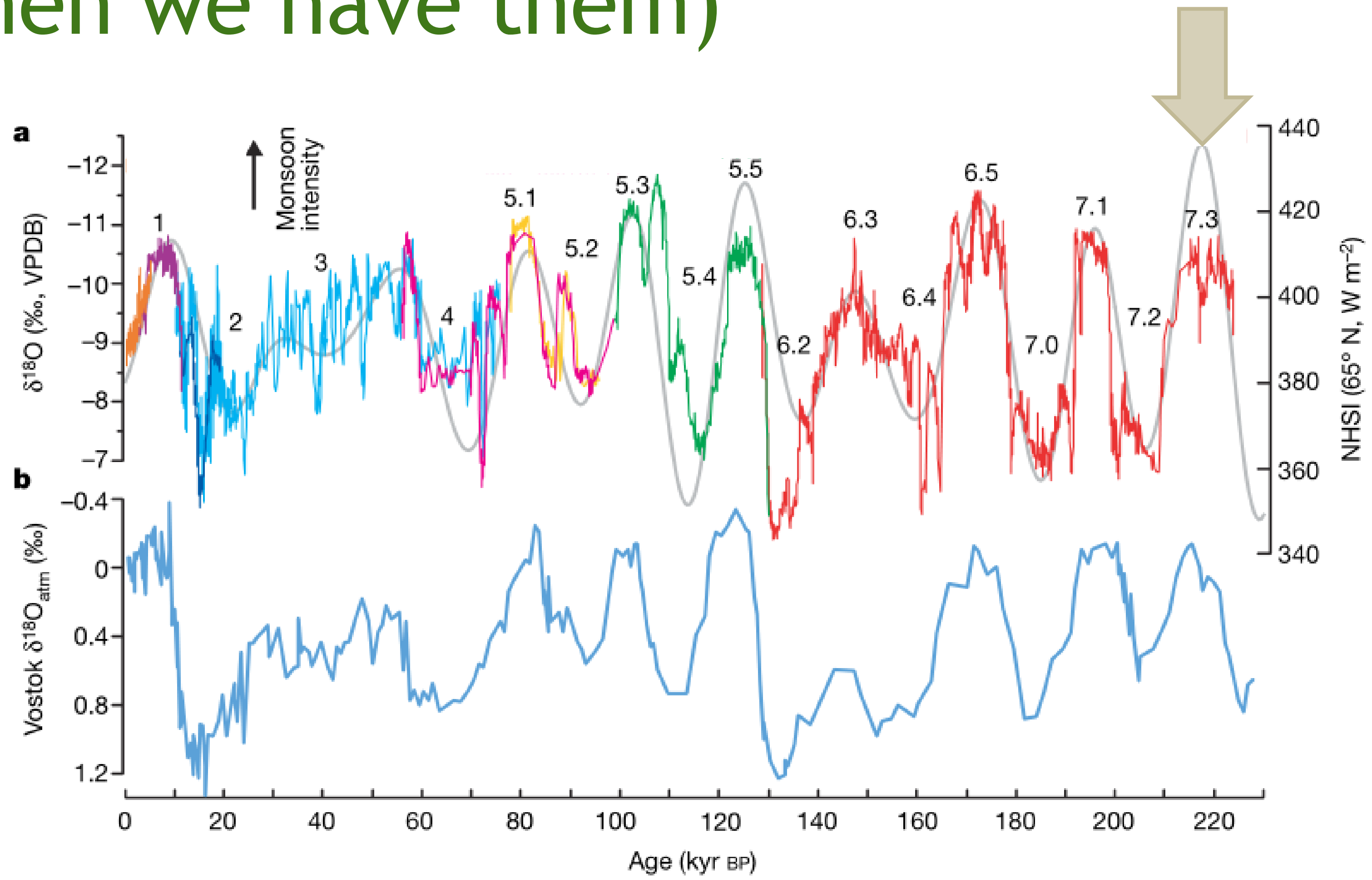


Wang et al., 2008

Figure 1 | Comparison of Sanbao/Hulu $\delta^{18}O$ records with NHSI and atmospheric $\delta^{18}O$ record over the past 224 kyr BP. a, Time versus Sanbao $\delta^{18}O$ records (red, stalagmite SB11; green, SB23; yellow, SB25-1; pink, SB22; dark blue, SB3; purple, SB10 and orange, SB26) and Hulu cave (blue)[2], and NHSI (Northern Hemisphere summer insolation, 21 July) at 65° N[10] (grey). For comparison, the Hulu $\delta^{18}O$ record is plotted 1.6‰ more negative to account for the higher Hulu values than Sanbao cave (see Supplementary Fig. 4). The ^{230}Th ages and errors (2σ error bars at top) are colour-coded by stalagmites. Numbers indicate the marine isotope stages and substages. **b**, The atmospheric $\delta^{18}O$ record from Vostok ice core, Antarctica[28].

Astronomical solutions (when we have them)

Grey line : Insolation curve of the 21st of July at 65°N



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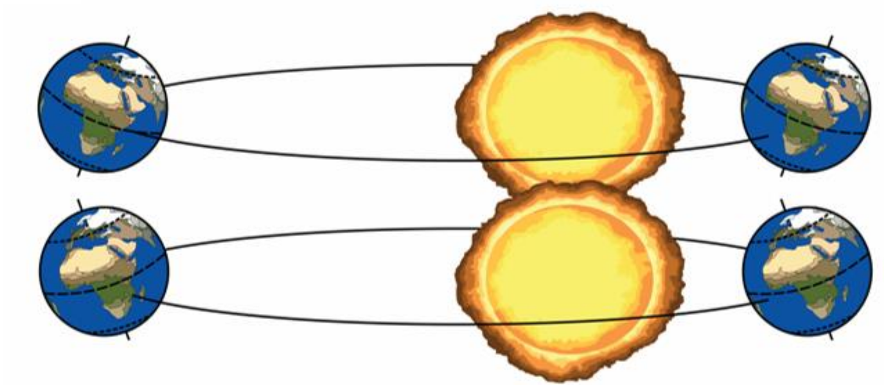
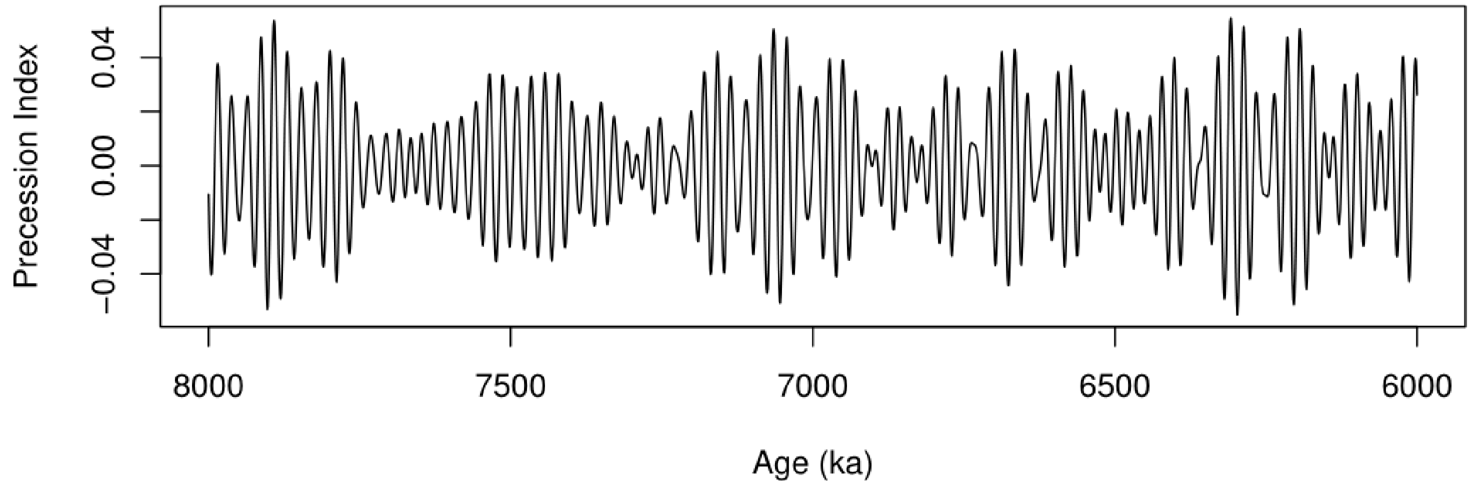
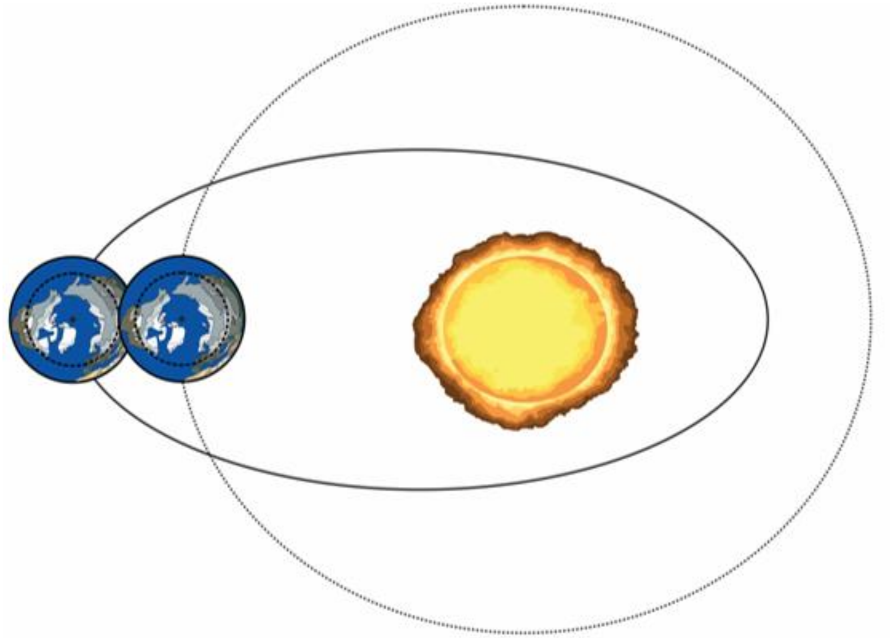
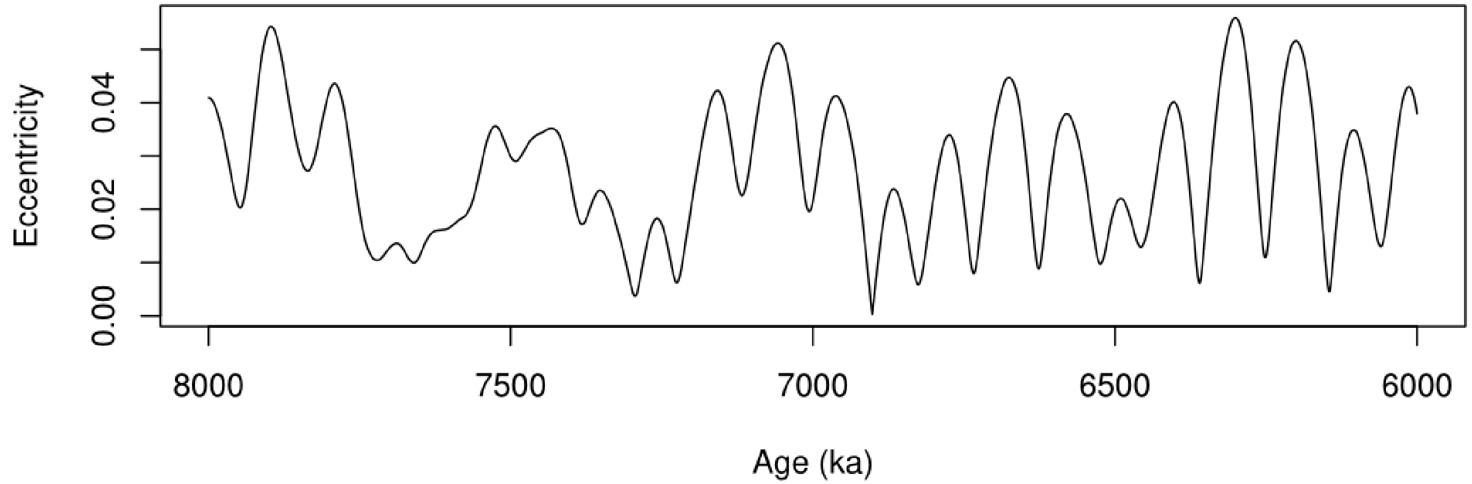
Amplitude modulations









Ratios of frequencies

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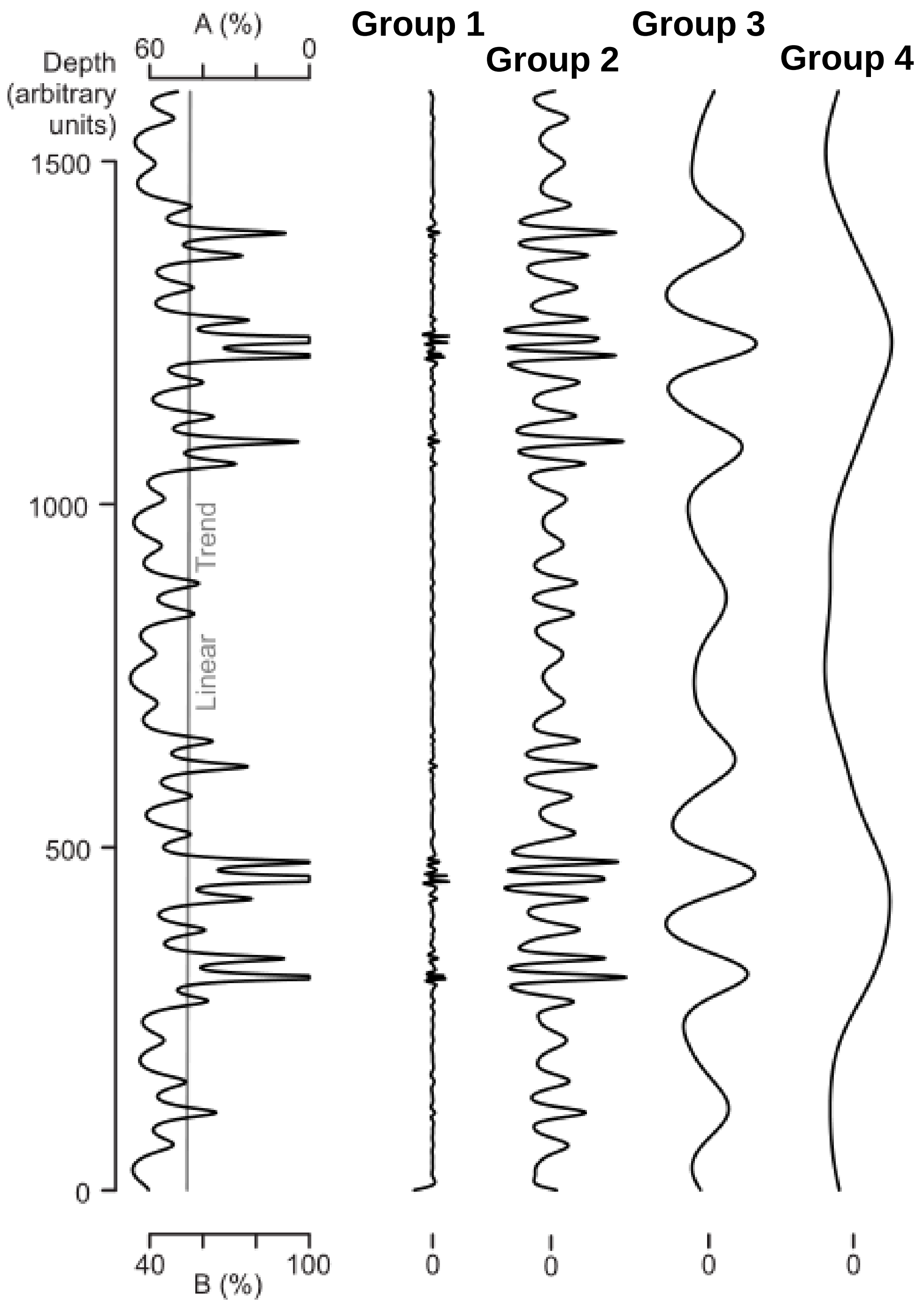

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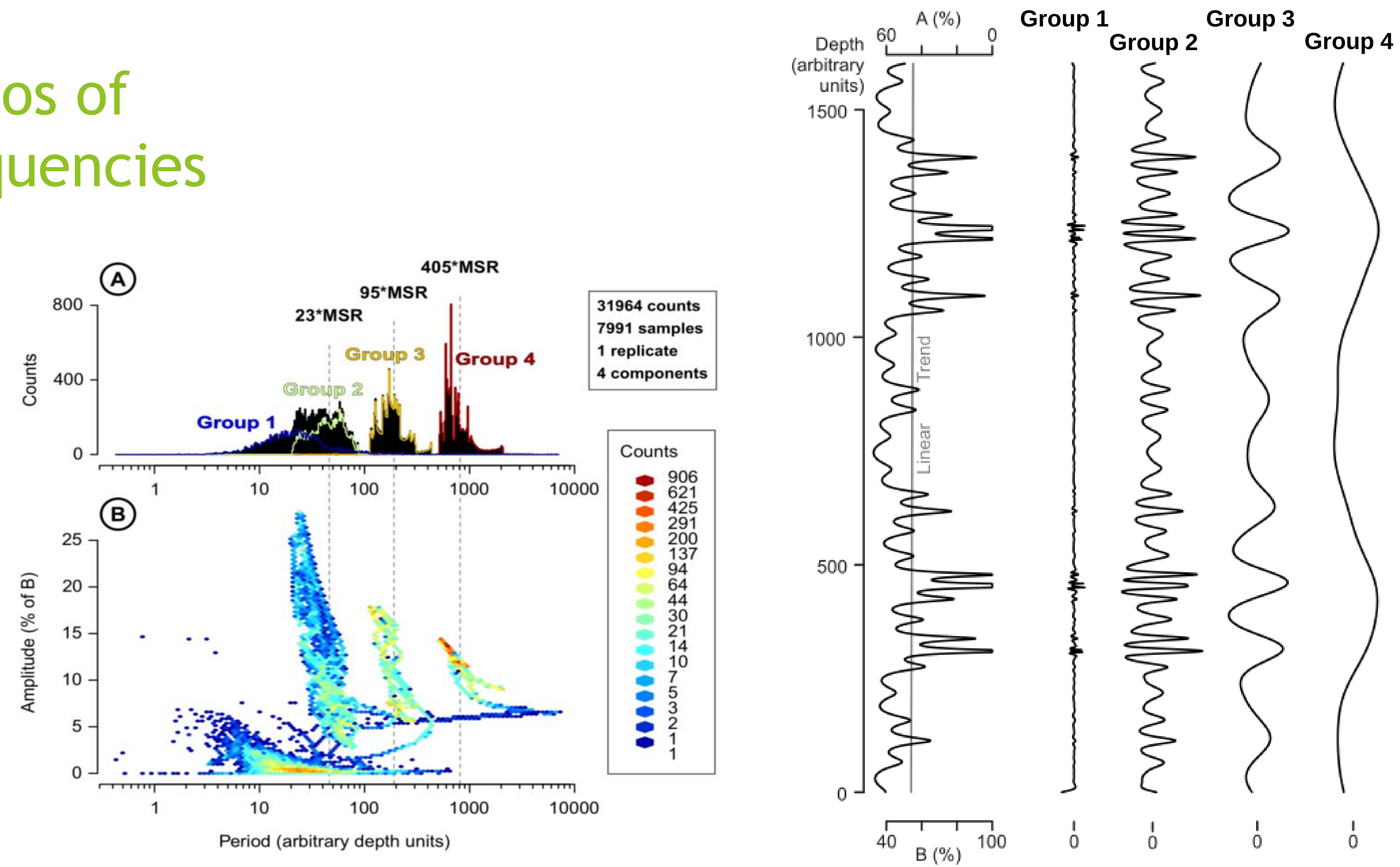

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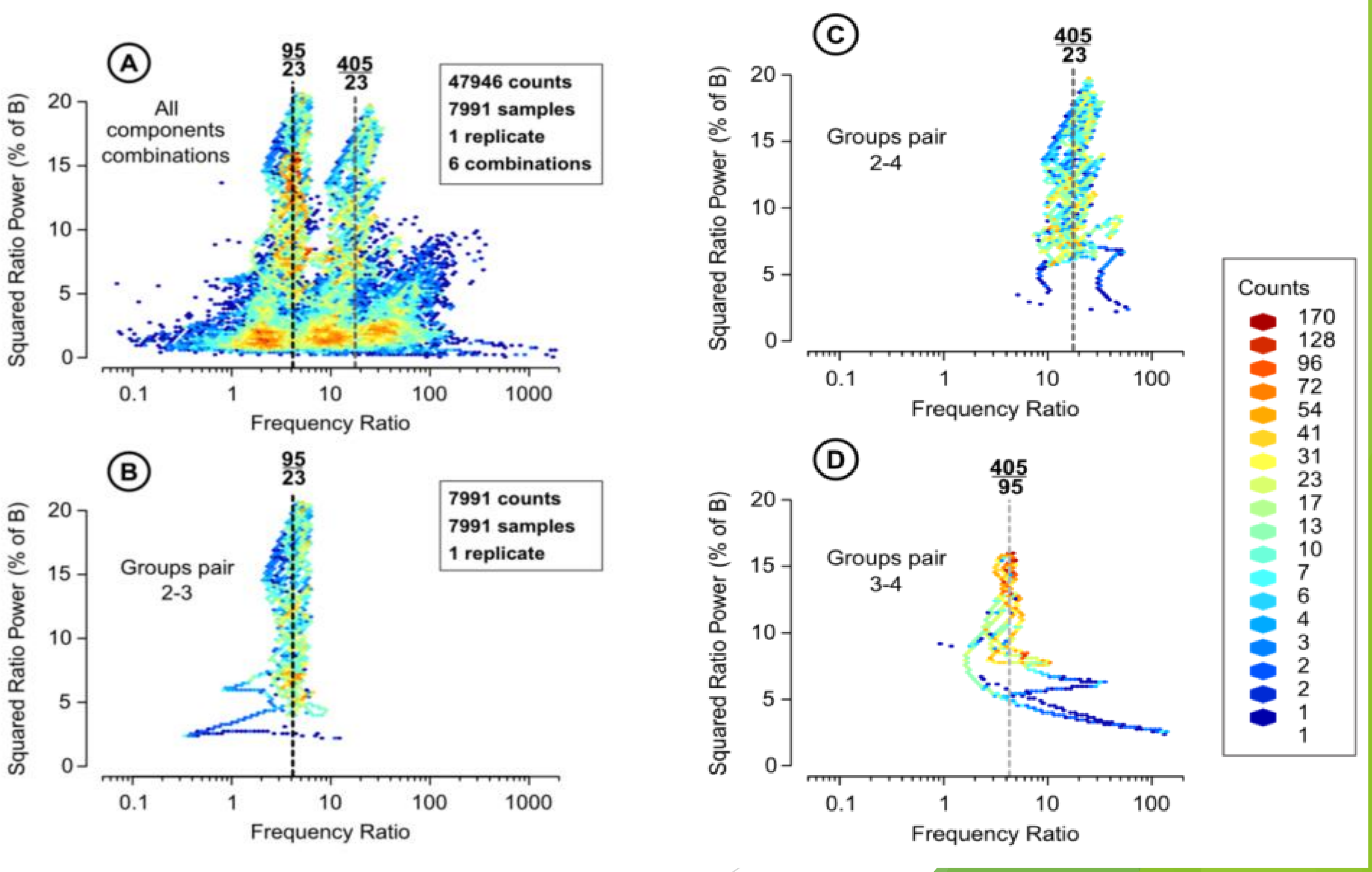
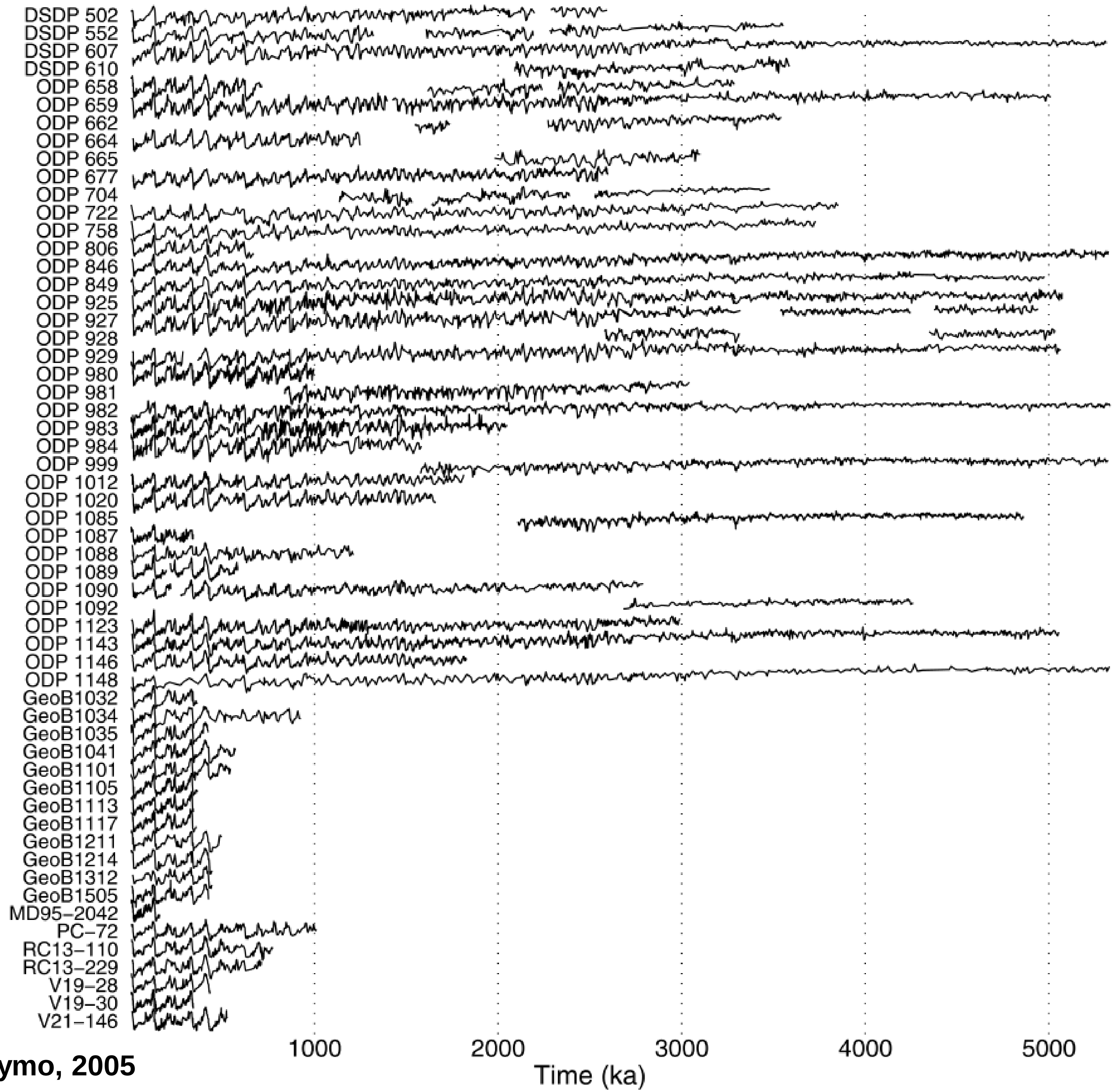


Other geological records

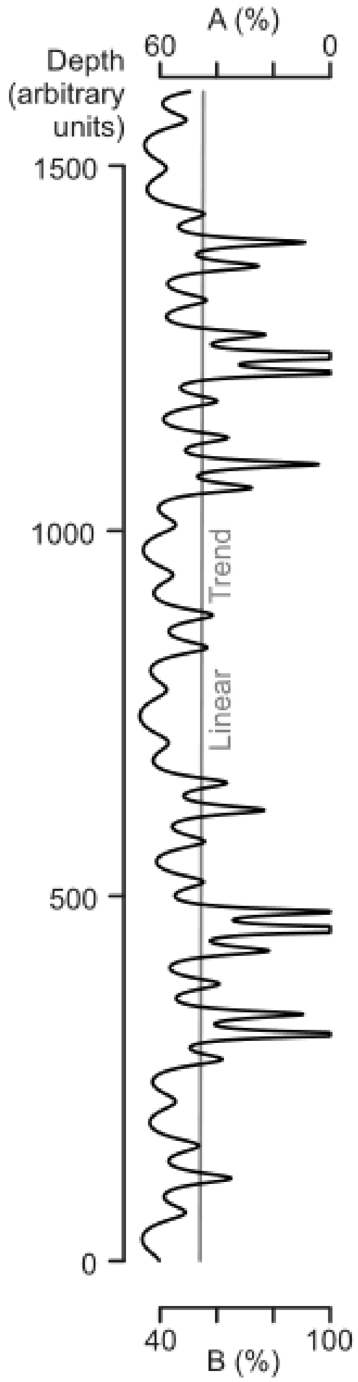
- The geological record should be coherent throughout the world for similar time periods



Lisiecki & Raymo, 2005

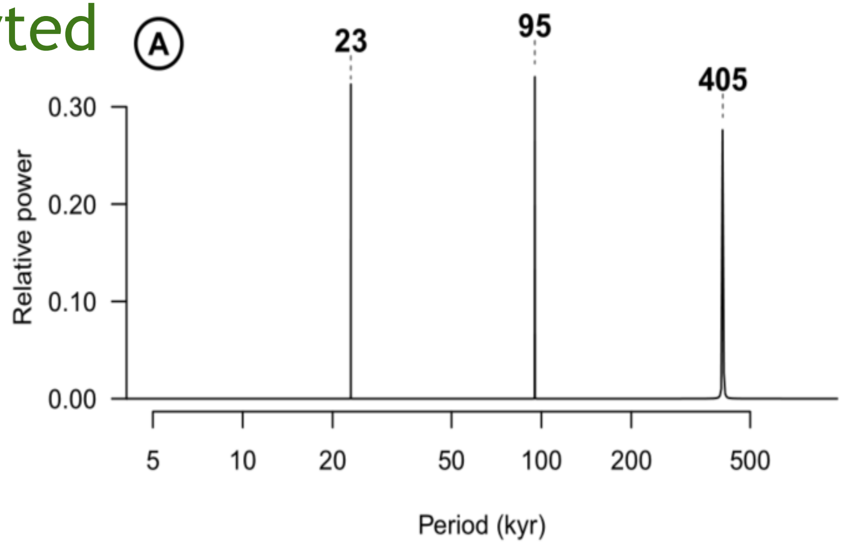
Disentangling the signal

Fourier spectra

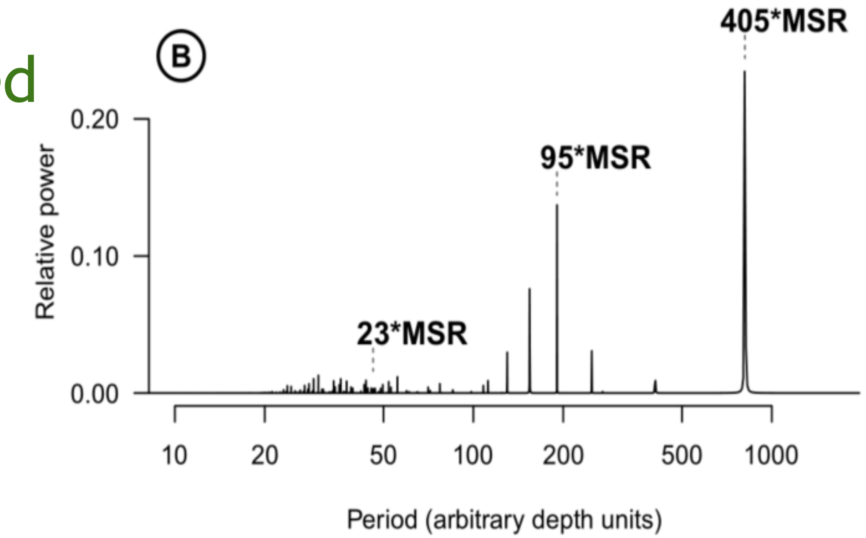


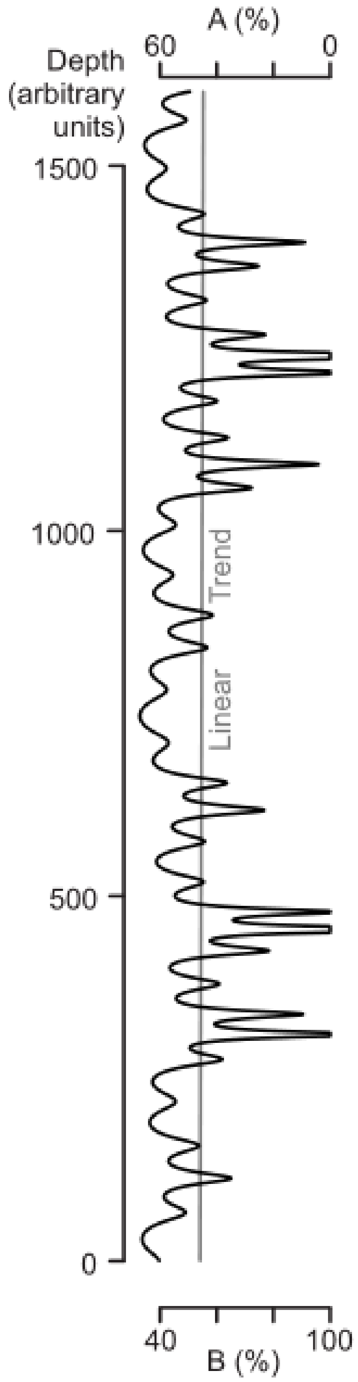
Fourier spectra

Undistorted

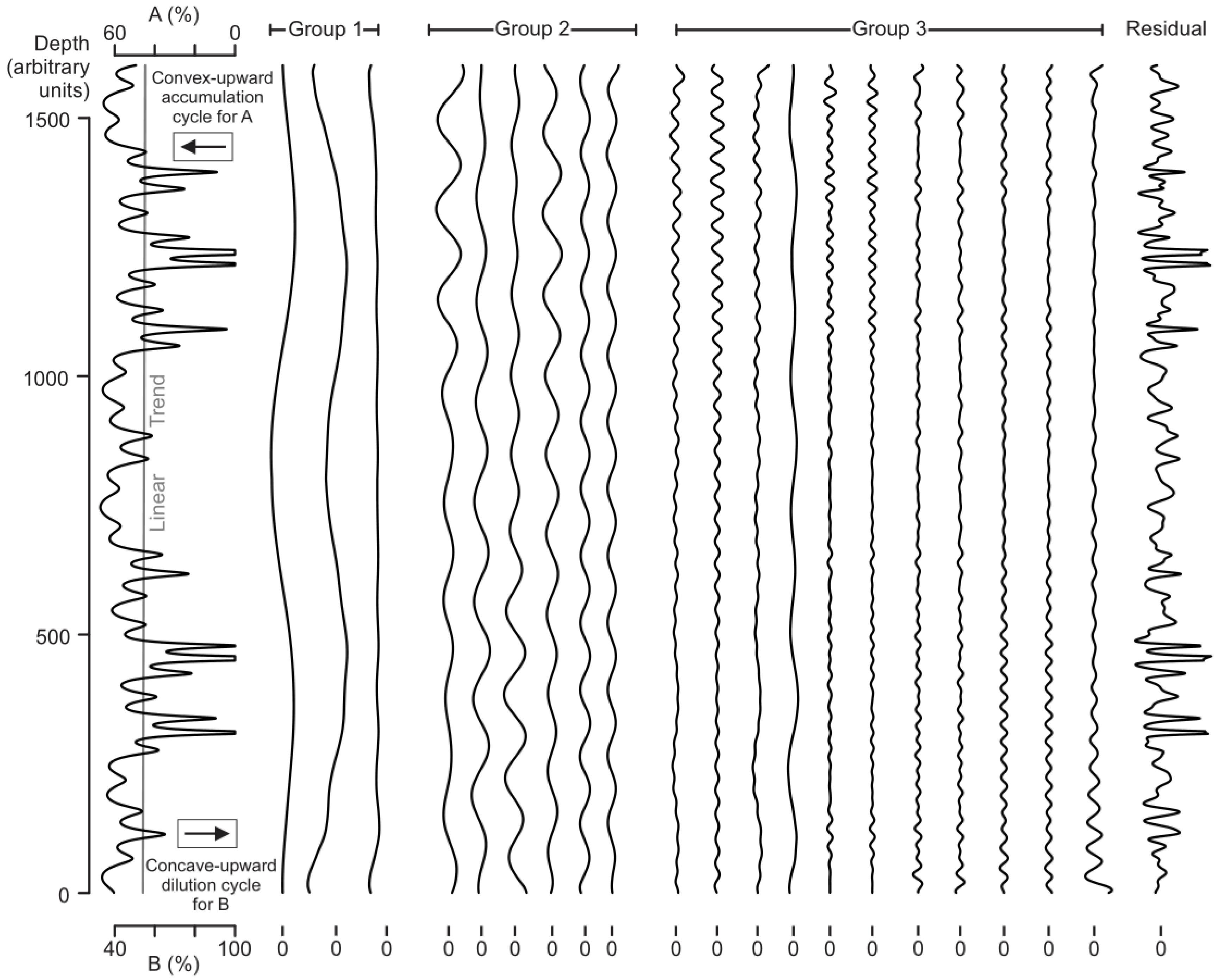


Depth-distorted

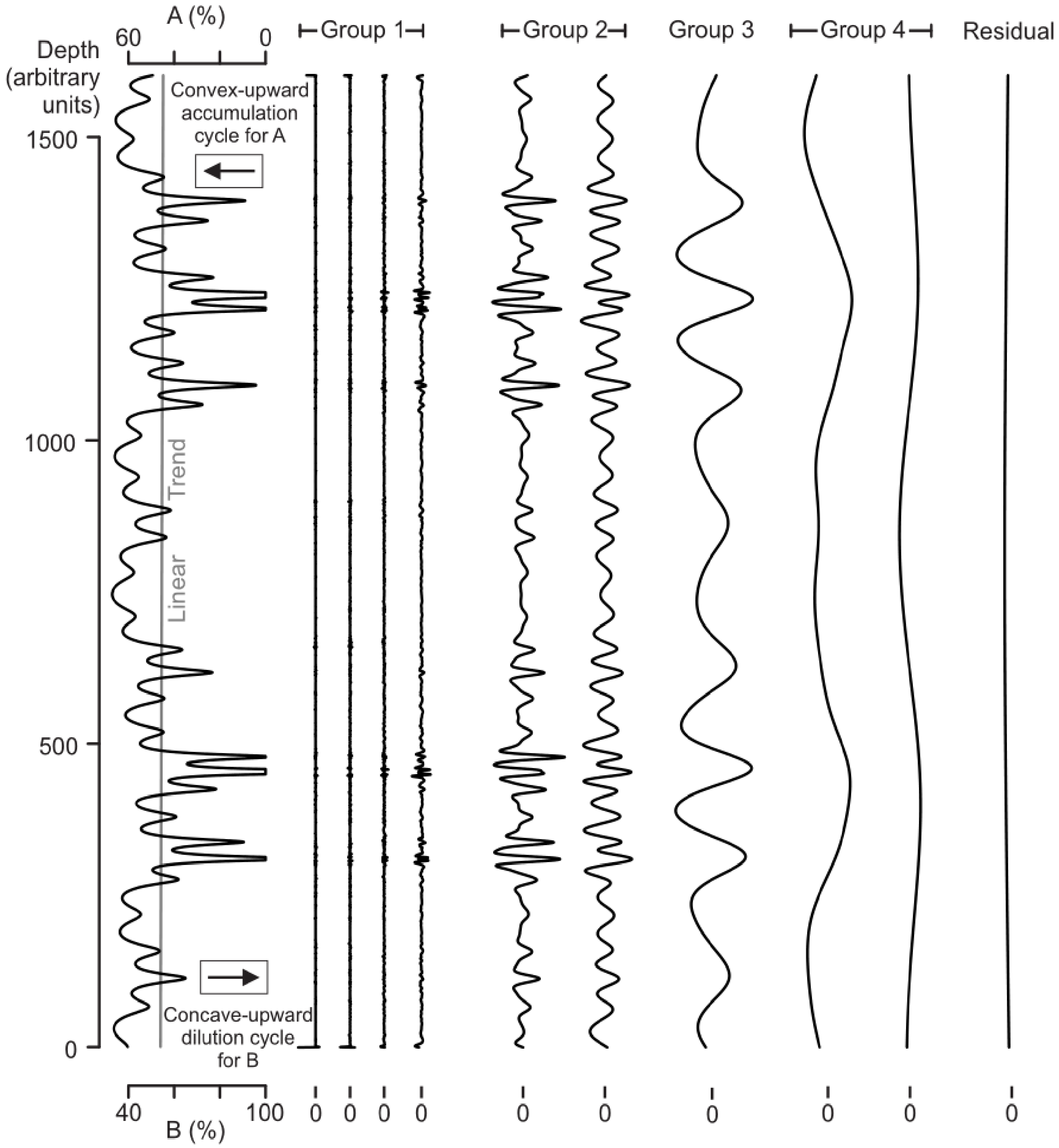




Singular Spectrum Analysis (SSA)

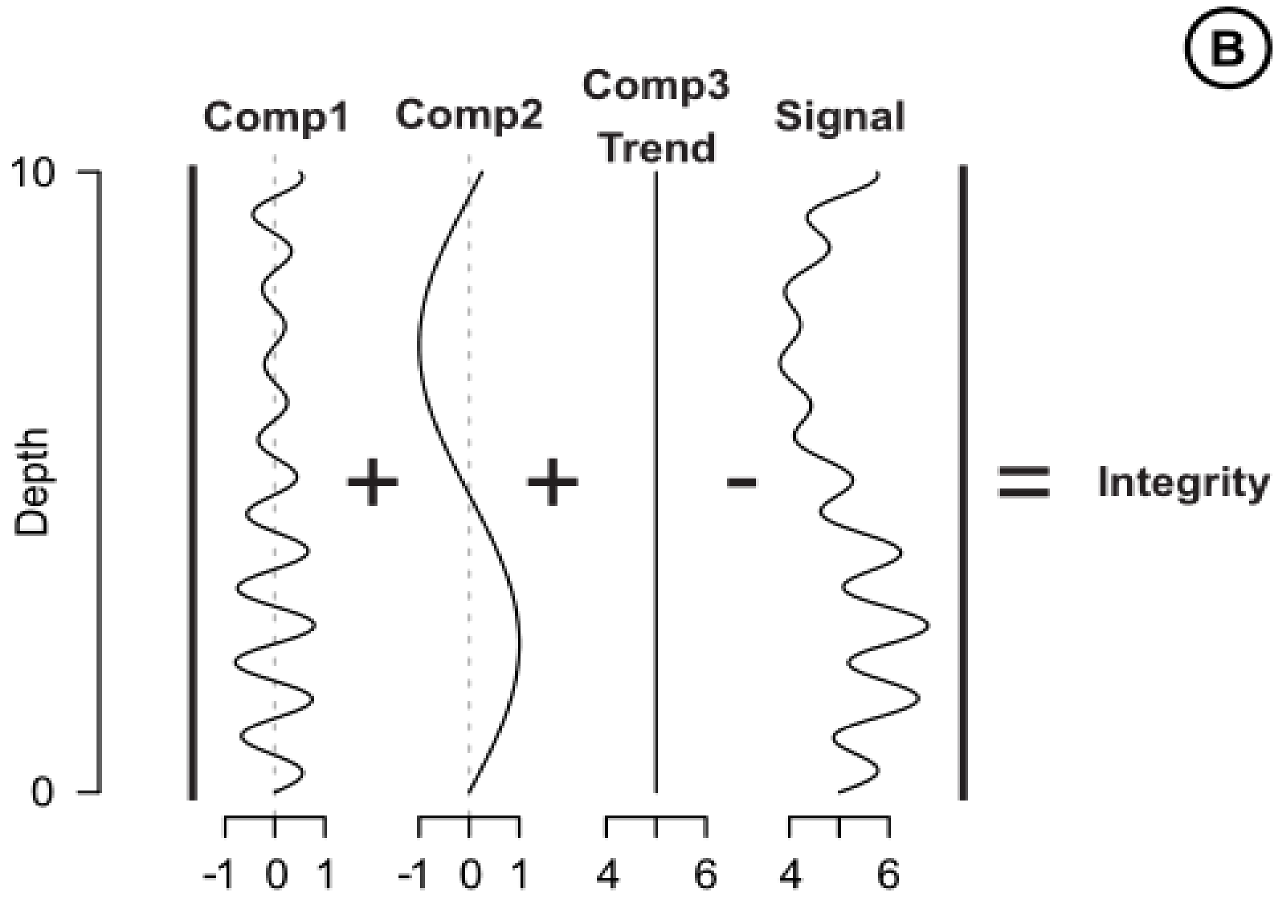


Ensemble Empirical Mode Decomposition (EEMD)

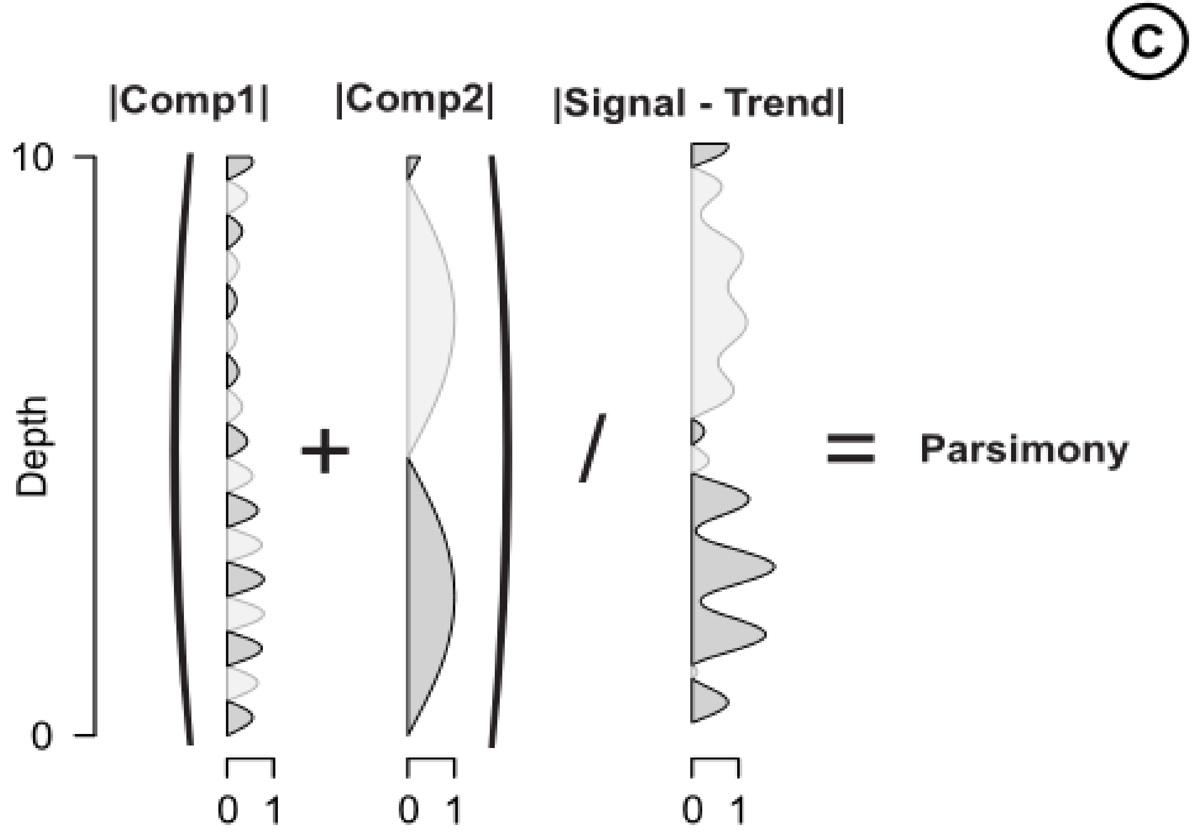


The advantages of decomposition: **Providing quality criterions for the representativity of the information**

Ability to quantify the loss of information



Ability to quantify the addition of spurious information



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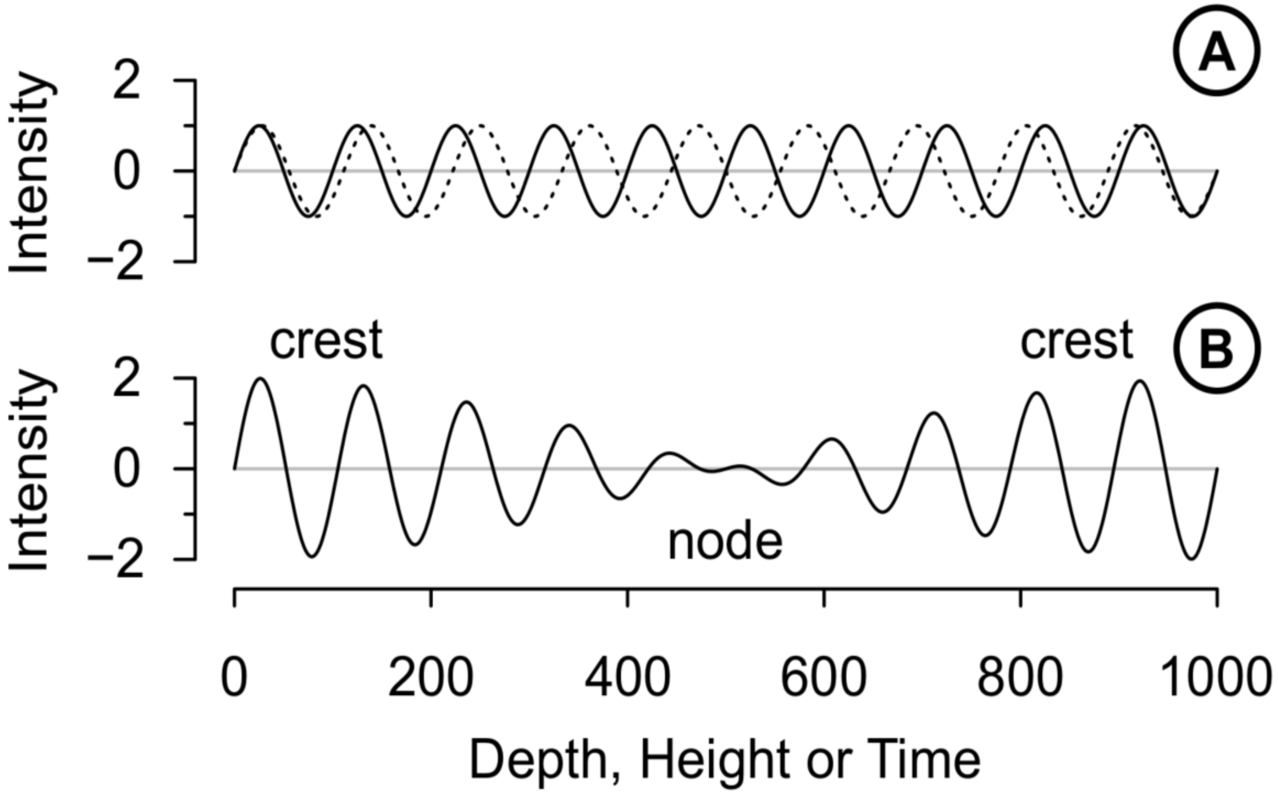
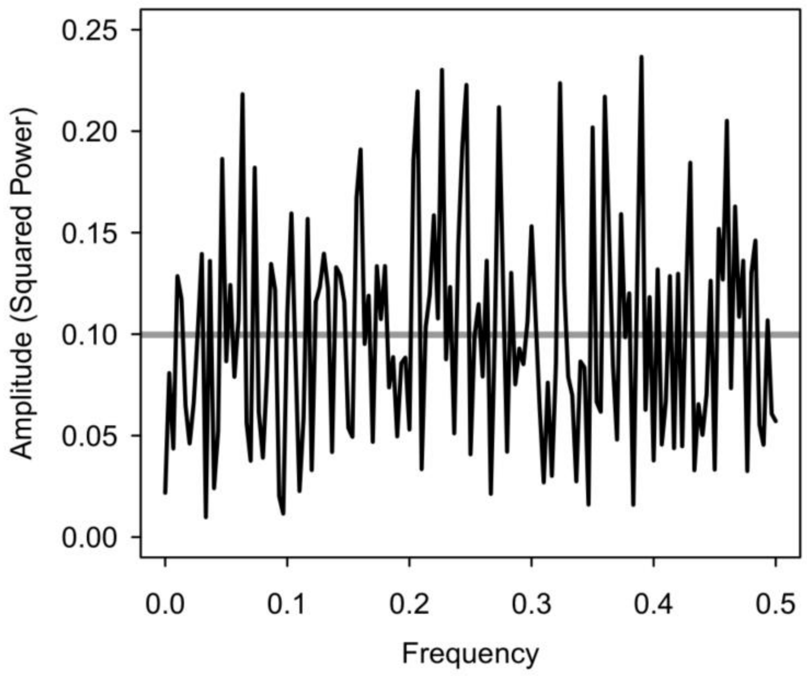
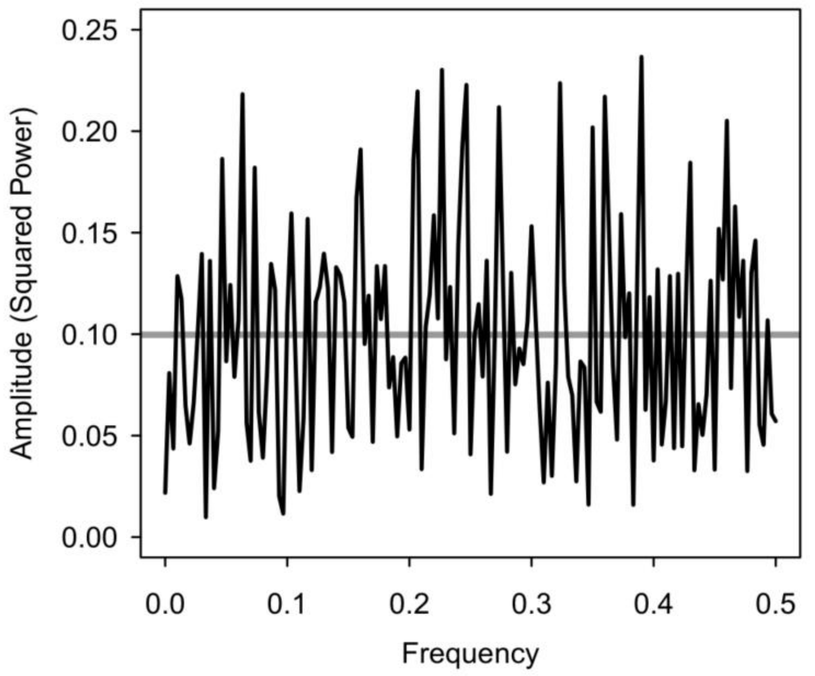




- Power spectra of a 300 points white noise signal.
- Parsimony: 12.26 (IN TIME DOMAIN OF A FOURIER **SERIES**)
- 1126 % absolute intensity in the decomposition in excess compared to the original signal



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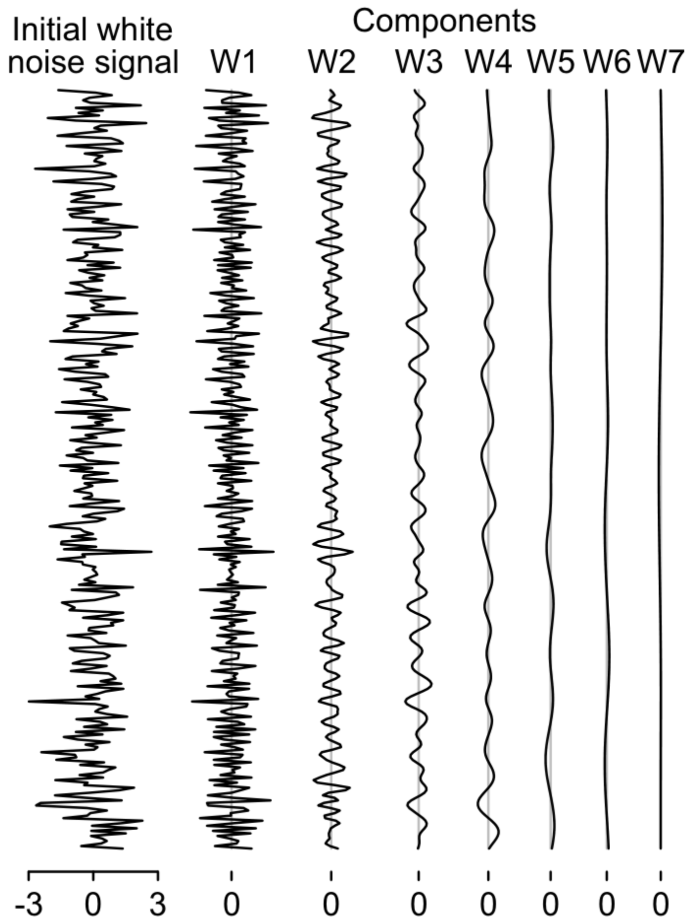
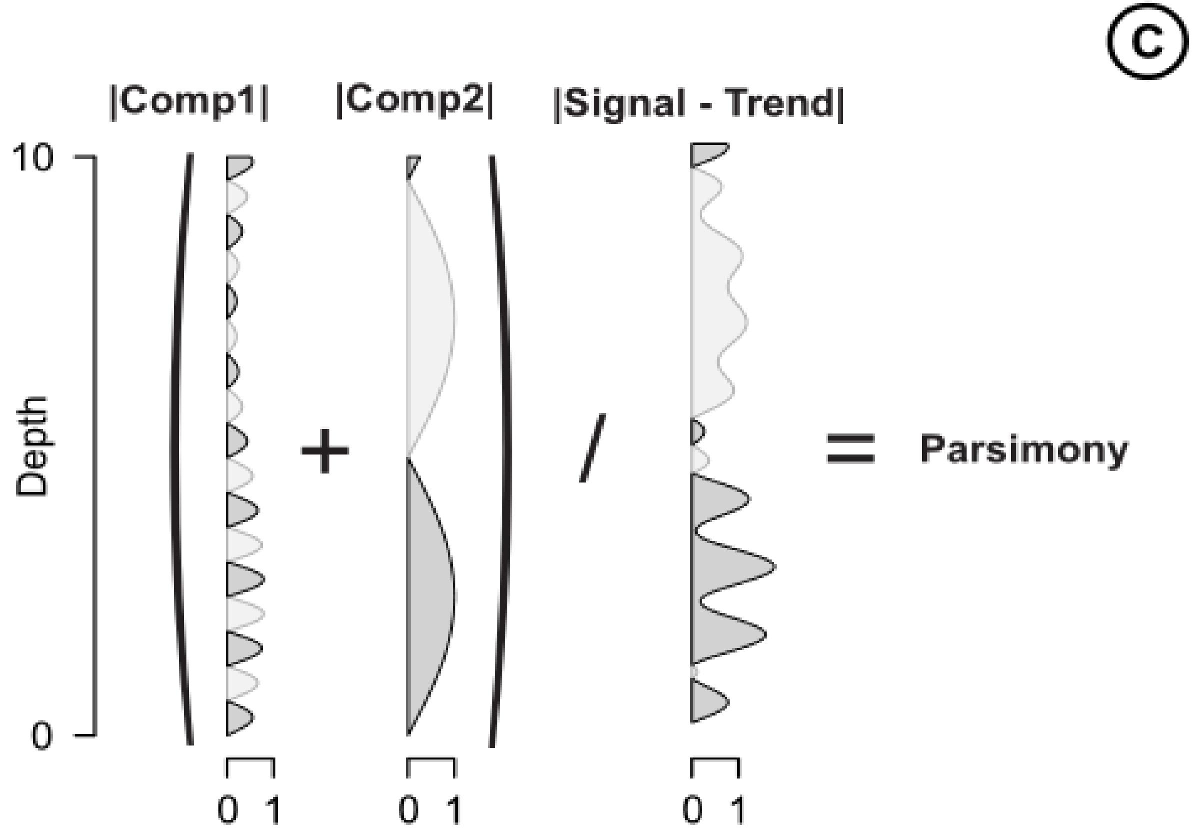


- EEMD decomposition of the same 300 points white noise signal.
- Parsimony: 1.74
- 74% excess absolute intensity

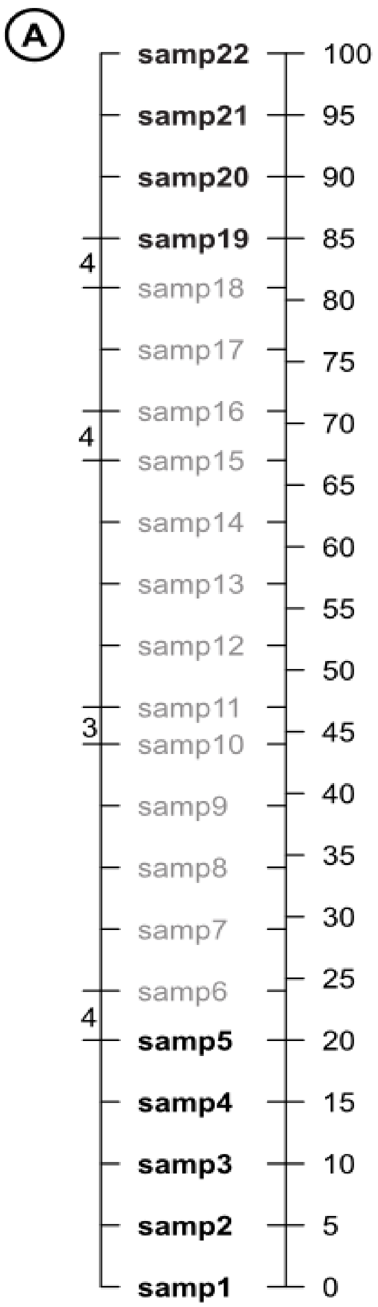
Ability to quantify the addition of spurious information



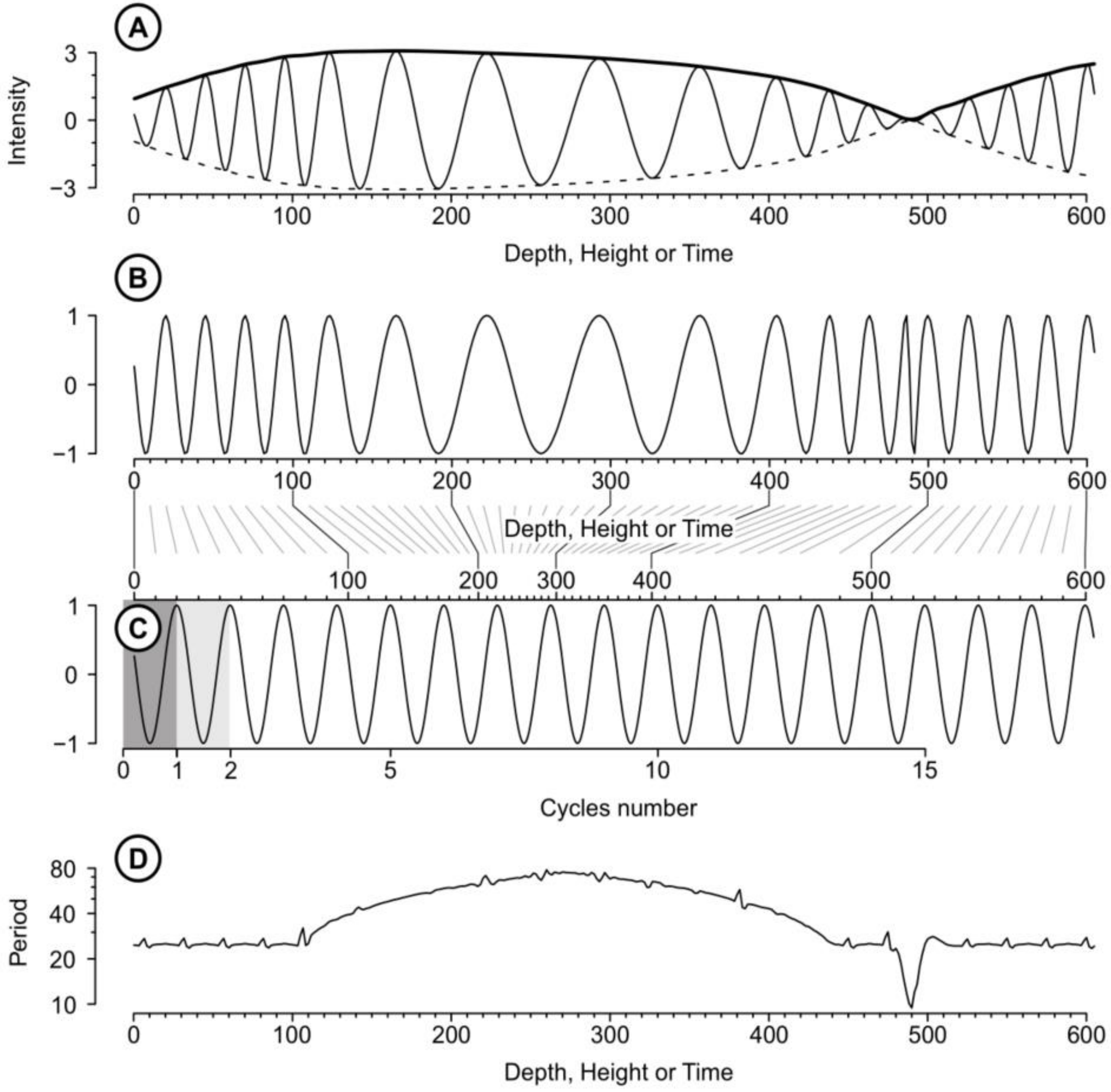
Ability to check whether the information was not changed (especially the position of samples)

- divisor(), in StratigrapheR package: R function to compute the **highest rational common divisor** of depth values to have regular resampling interval preserving the data points

- Concept of reversibility: reconstructing the input exactly how it was, from the output

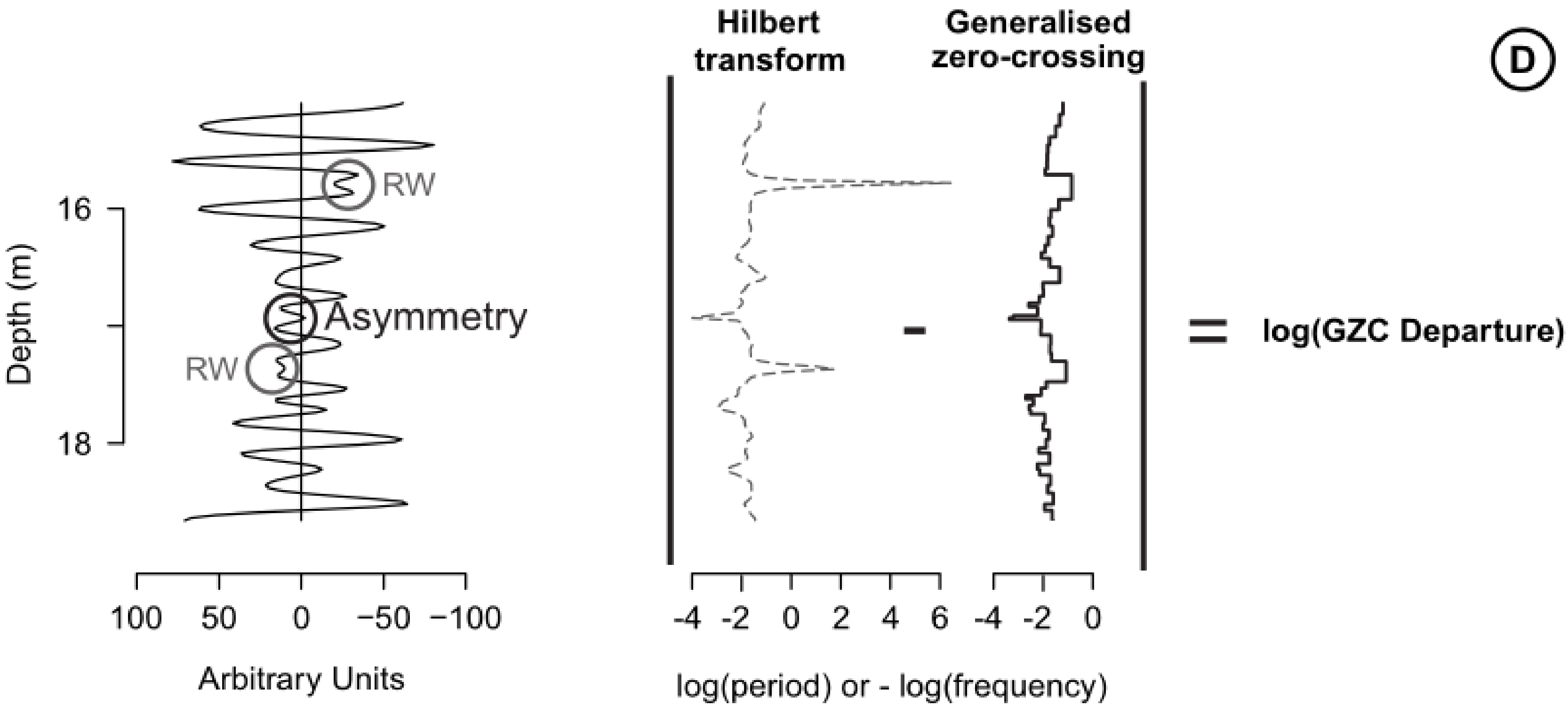


Ability to extract the instantaneous frequency



Ability to provide an error on the instantaneous frequency

- Generalised Zero-Crossing Departure



Ability to provide an error on the instantaneous frequency

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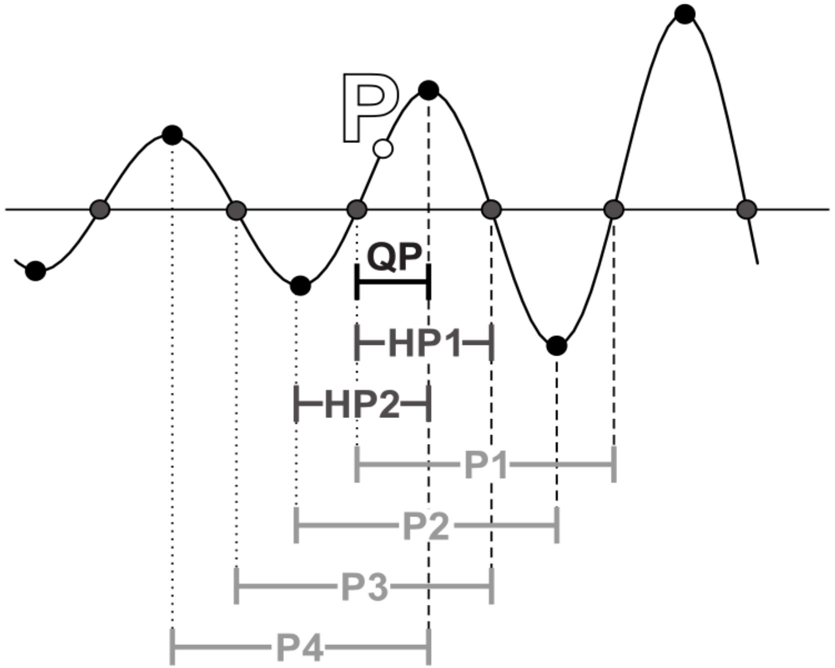

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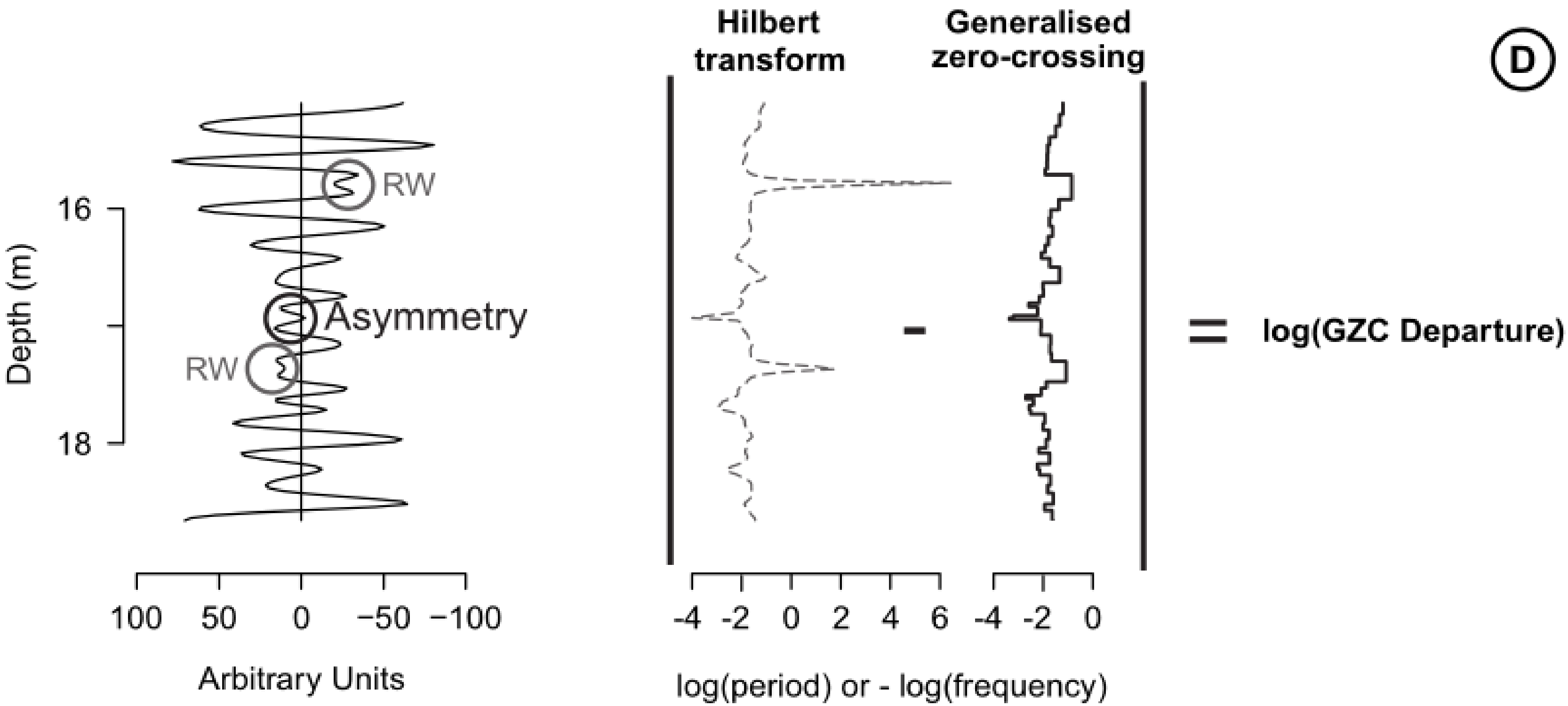
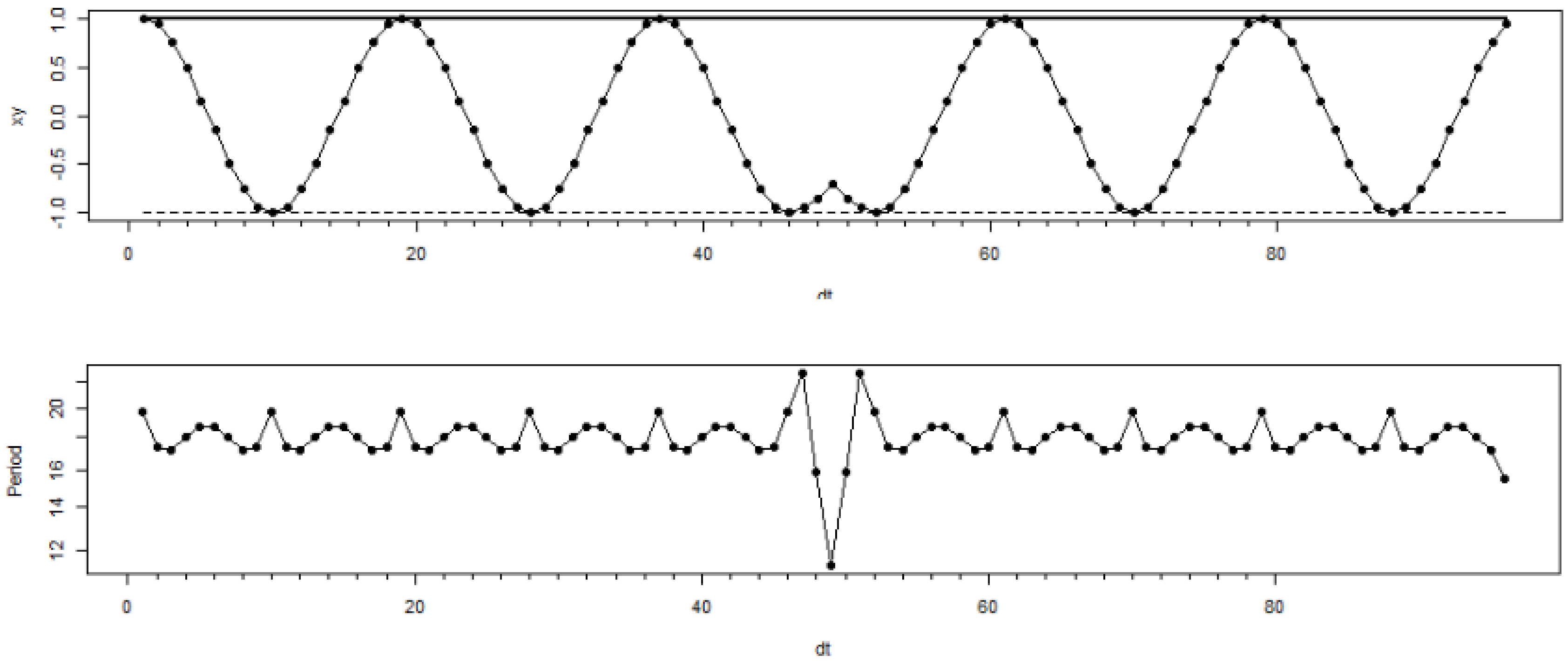


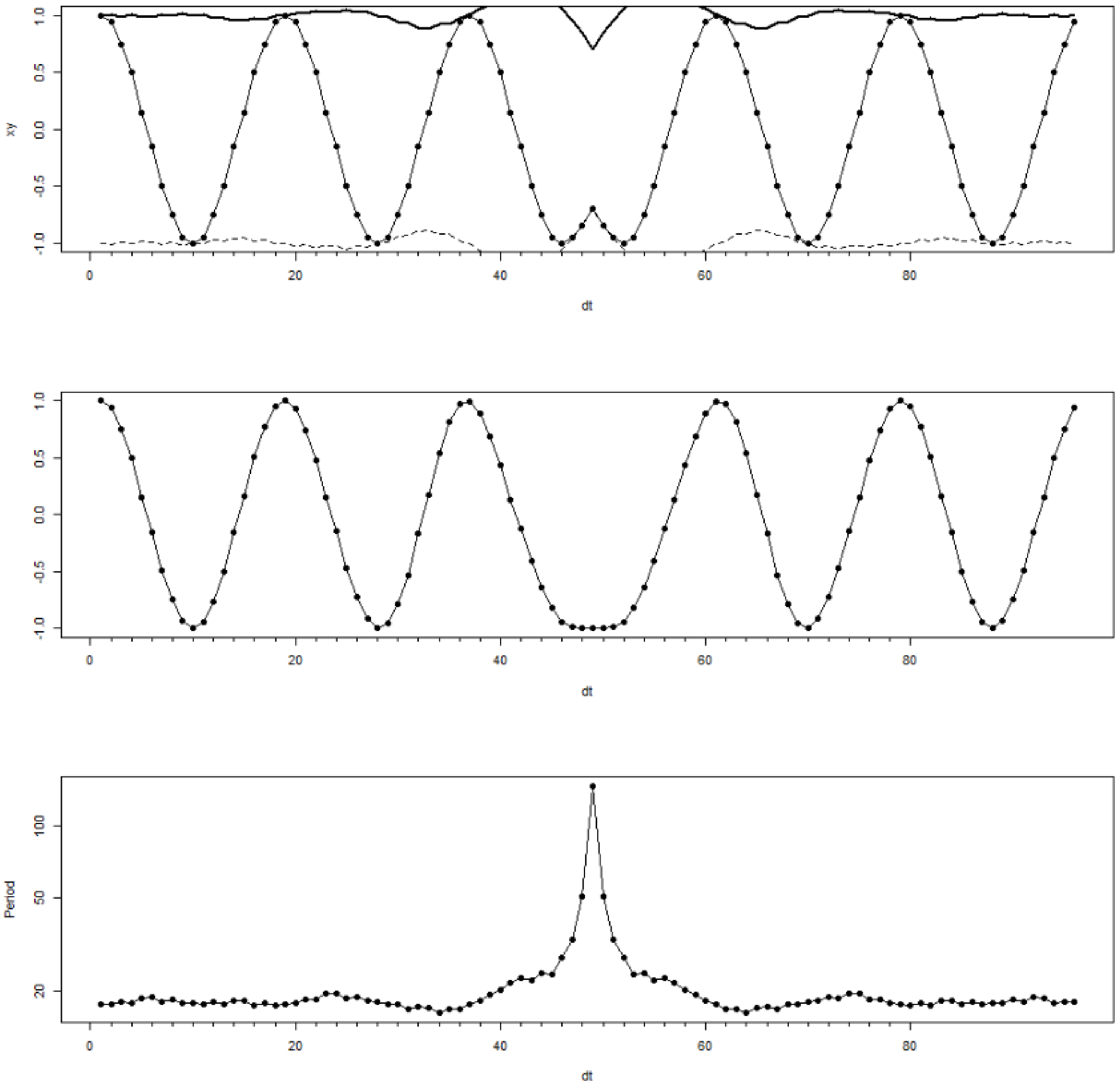
Ability to provide an error on the instantaneous frequency

Riding wave on direct quadrature instantaneous frequency estimation



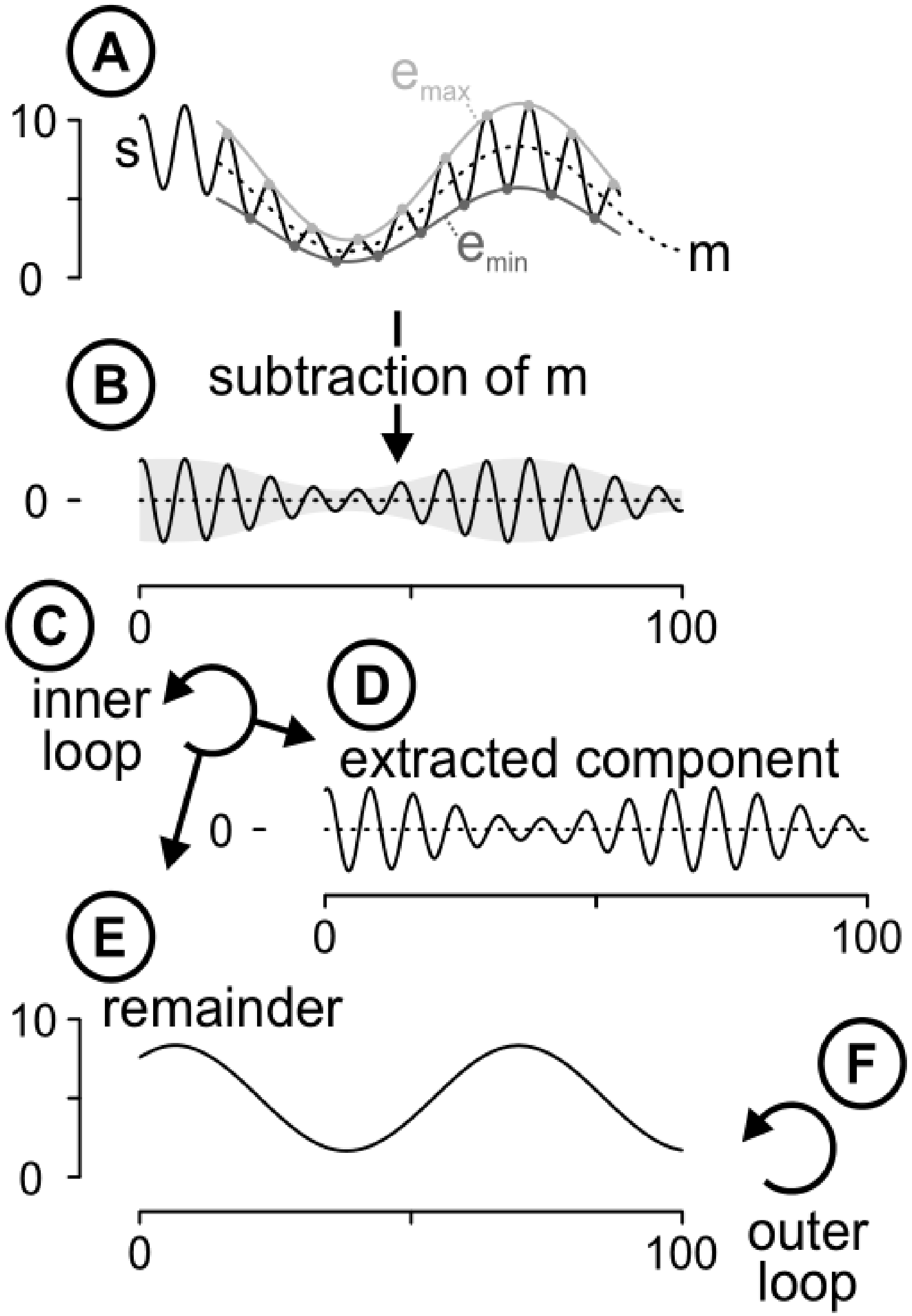
Ability to provide an error on the instantaneous frequency

Riding wave on Hilbert transform-based instantaneous frequency estimation



An EEMD algorithm to preserve integrity (and to go fast, for short-scale data)

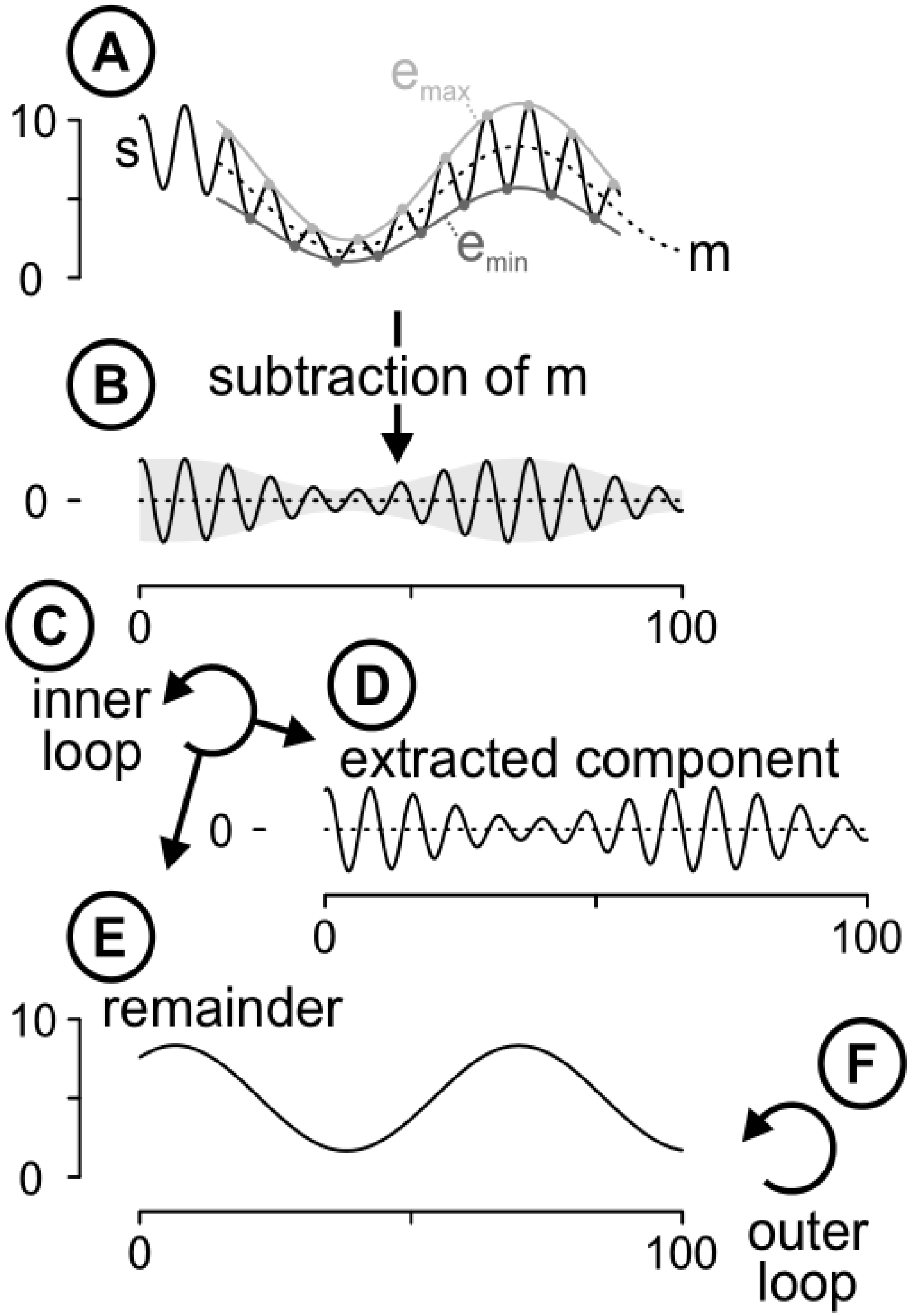
EMD algorithm



EEMD algorithm

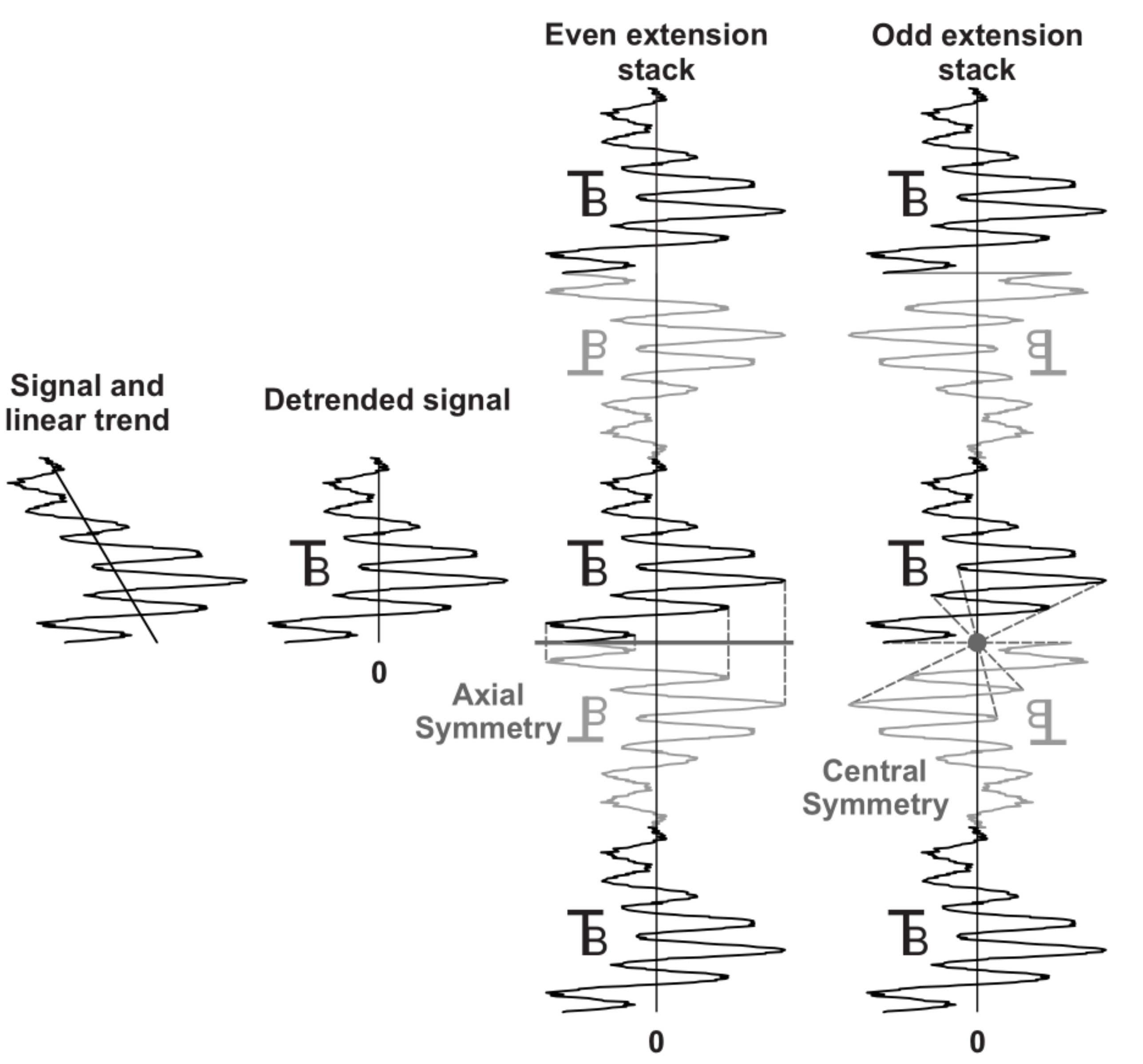
ENSEMBLE Empirical Mode Decomposition

- Same thing than EMD, but with several white-noise added realisations
- Reduces mixing of different scale wiggles (or mode mixing)



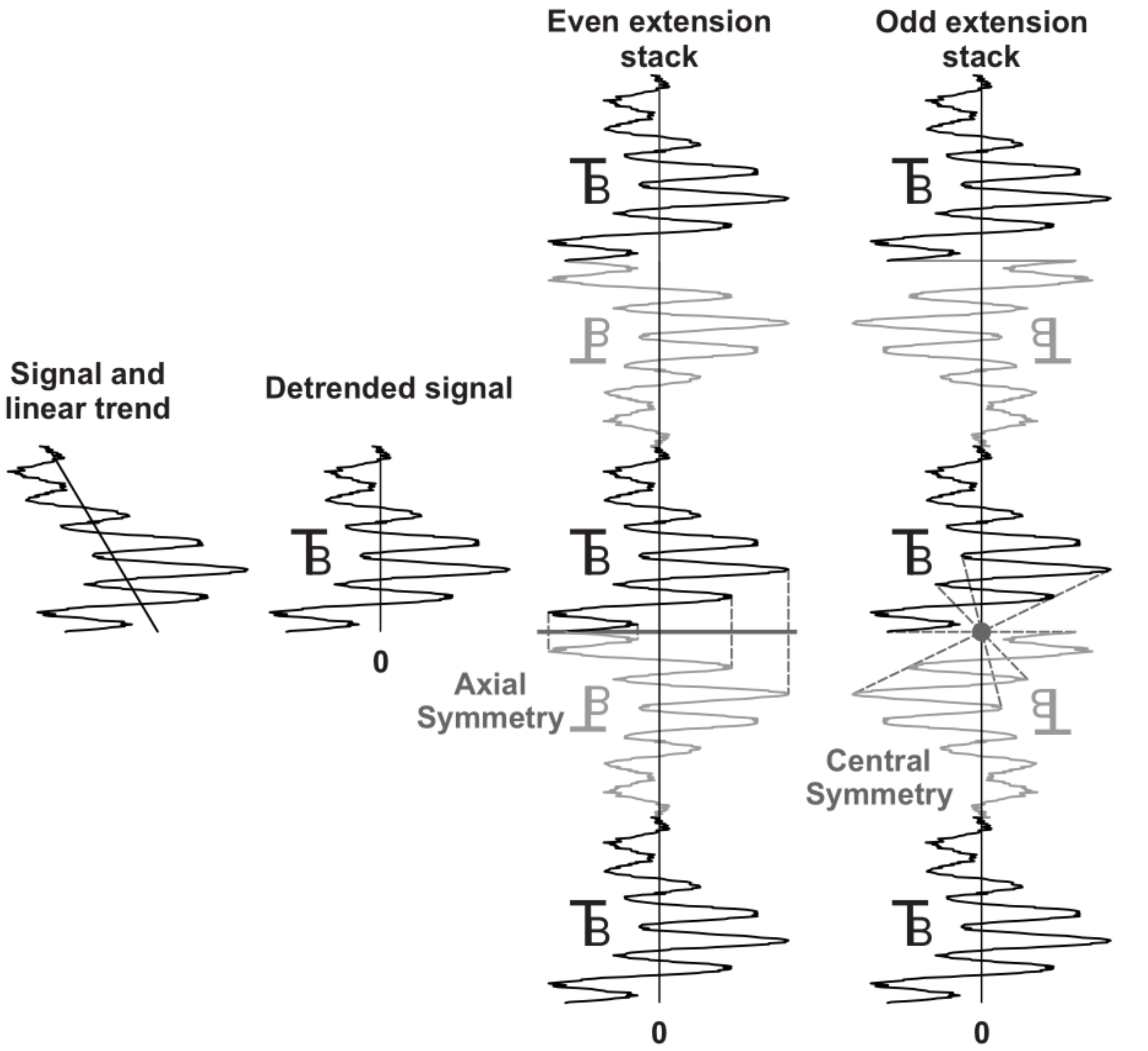
Extricate algorithm (in R)

- Splicing of even-odd extensions
- Only 2 iterations of EMD



Extricate algorithm (in R)

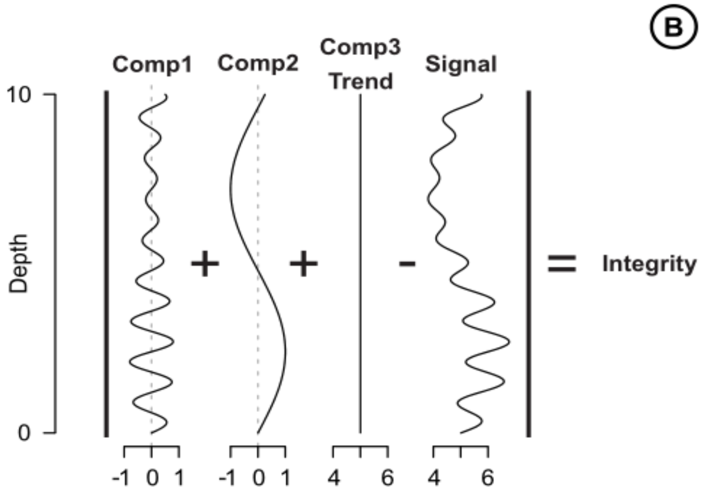
- Splicing of even-odd extensions
- Only 2 iterations of EMD
- White noise added in the even splice is inverted (negative) in the odd extension splice
- **Perfect integrity**
- **Less realizations needed for representative decomposition**



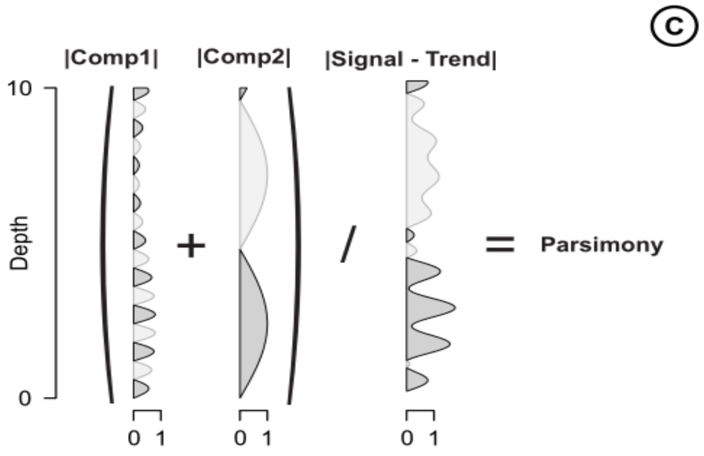
Conclusion

Conclusion

- Loss of information



- Addition of spurious information



- Disentangling the information


Thank you for your attention ☺

References

- Huybers, Peter, and William Curry. 2006. 'Links between Annual, Milankovitch and Continuum Temperature Variability'. *Nature* 441 (7091): 329–32. https://doi.org/10.1038/nature04745.
- Lisiecki, Lorraine E., and Maureen E. Raymo. 2005. 'A Pliocene-Pleistocene Stack of 57 Globally Distributed Benthic Δ18O Records'. *Paleoceanography* 20 (1). https://doi.org/10.1029/2004PA001071.
- Mazumder, Rajat, and Makoto Arima. 2005. 'Tidal Rhythmites and Their Implications'. *Earth-Science Reviews* 69 (1): 79–95. https://doi.org/10.1016/j.earscirev.2004.07.004.
- Wang, Yongjin, Hai Cheng, R. Lawrence Edwards, Xinggong Kong, Xiaohua Shao, Shitao Chen, Jiangyin Wu, Xiouyang Jiang, Xianfeng Wang, and Zhisheng An. 2008. 'Millennial- and Orbital-Scale Changes in the East Asian Monsoon over the Past 224,000 Years'. *Nature* 451 (7182): 1090–93. https://doi.org/10.1038/nature06692.
- Westphal, H., J. Lavi, and A. Munnecke. 2015. 'Diagenesis Makes the Impossible Come True: Intersecting Beds in Calcareous Turbidites'. *Facies* 61 (2): 3. https://doi.org/10.1007/s10347-015-0427-7.