



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

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Context

The background features a complex, abstract design of overlapping, semi-transparent green polygons. The colors range from a light, pale green to a deep, dark forest green. The shapes are primarily triangular and quadrilateral, creating a sense of depth and movement. The design is concentrated on the right side of the frame, with the left side being mostly white.

Introduction

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



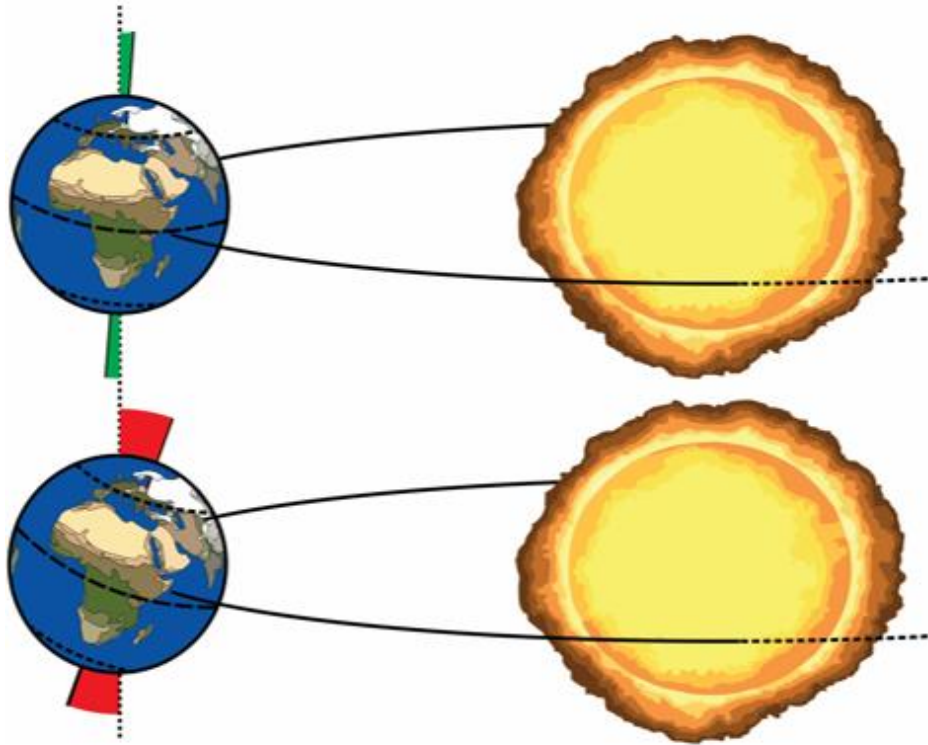
Mazumder & Arima, 2005



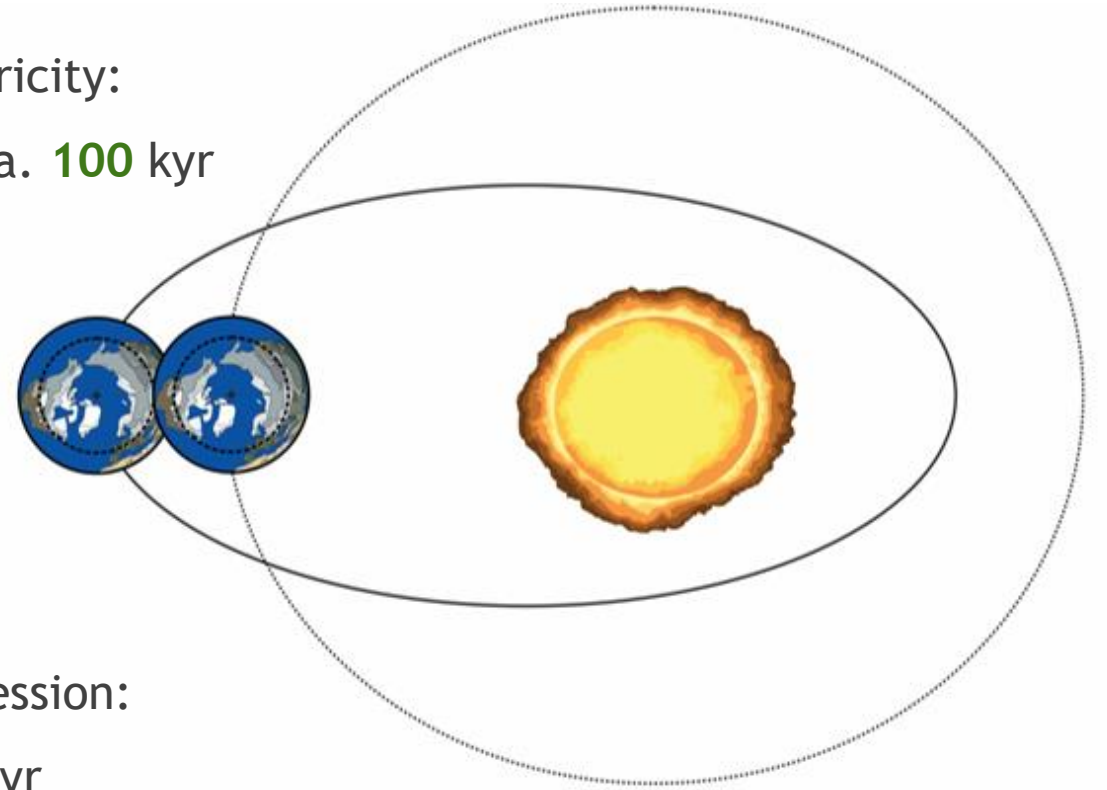
Photo credit: www.southampton.ac.uk

Astronomical cycles

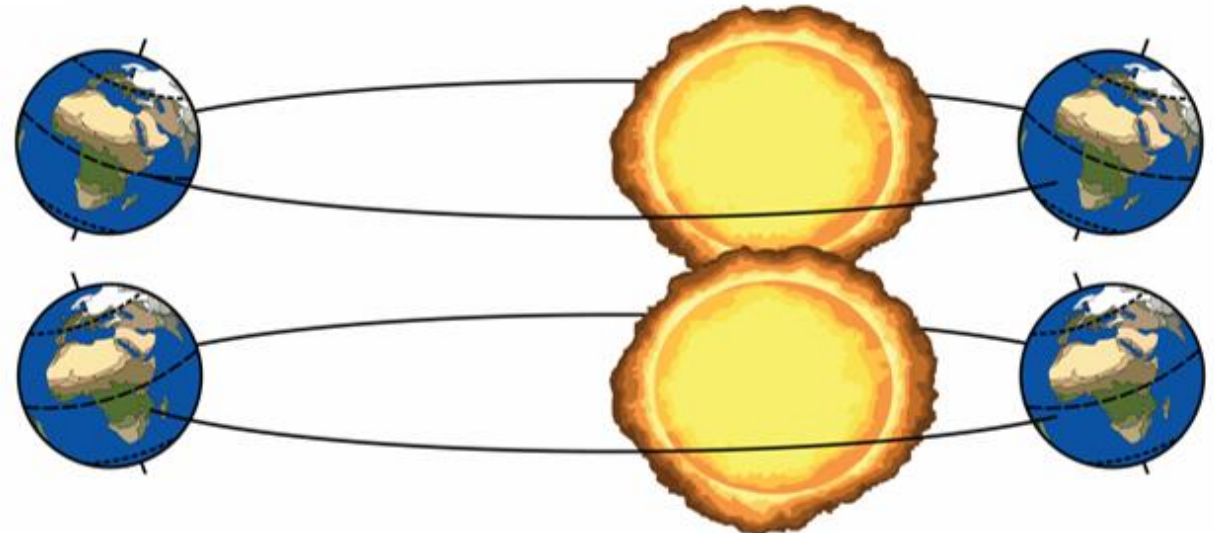
- ▶ Obliquity
Ca. 40 kyr



- ▶ Eccentricity:
405 and ca. 100 kyr

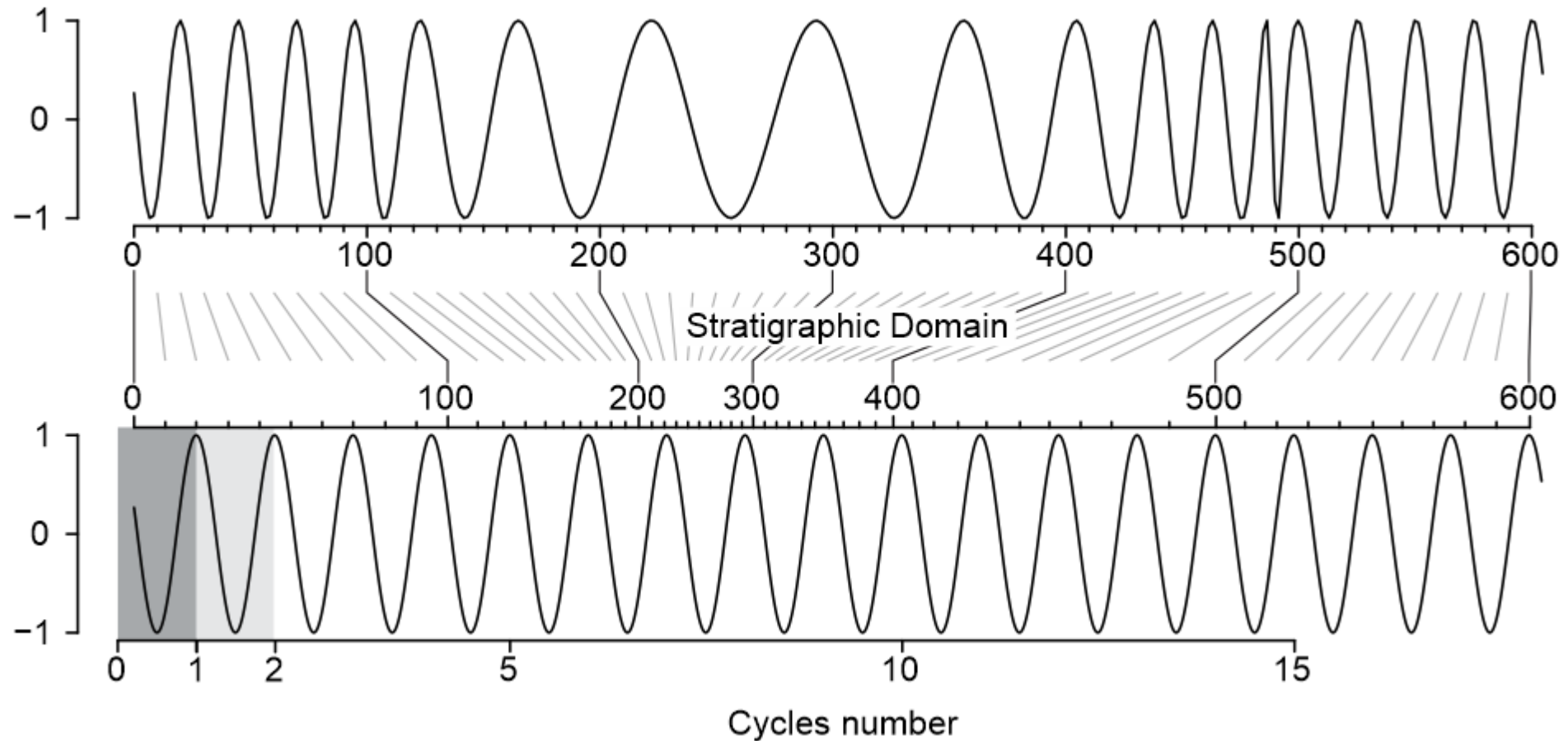


- ▶ Precession:
Ca. 20 kyr



What are the problems to identify astronomical cycles ?

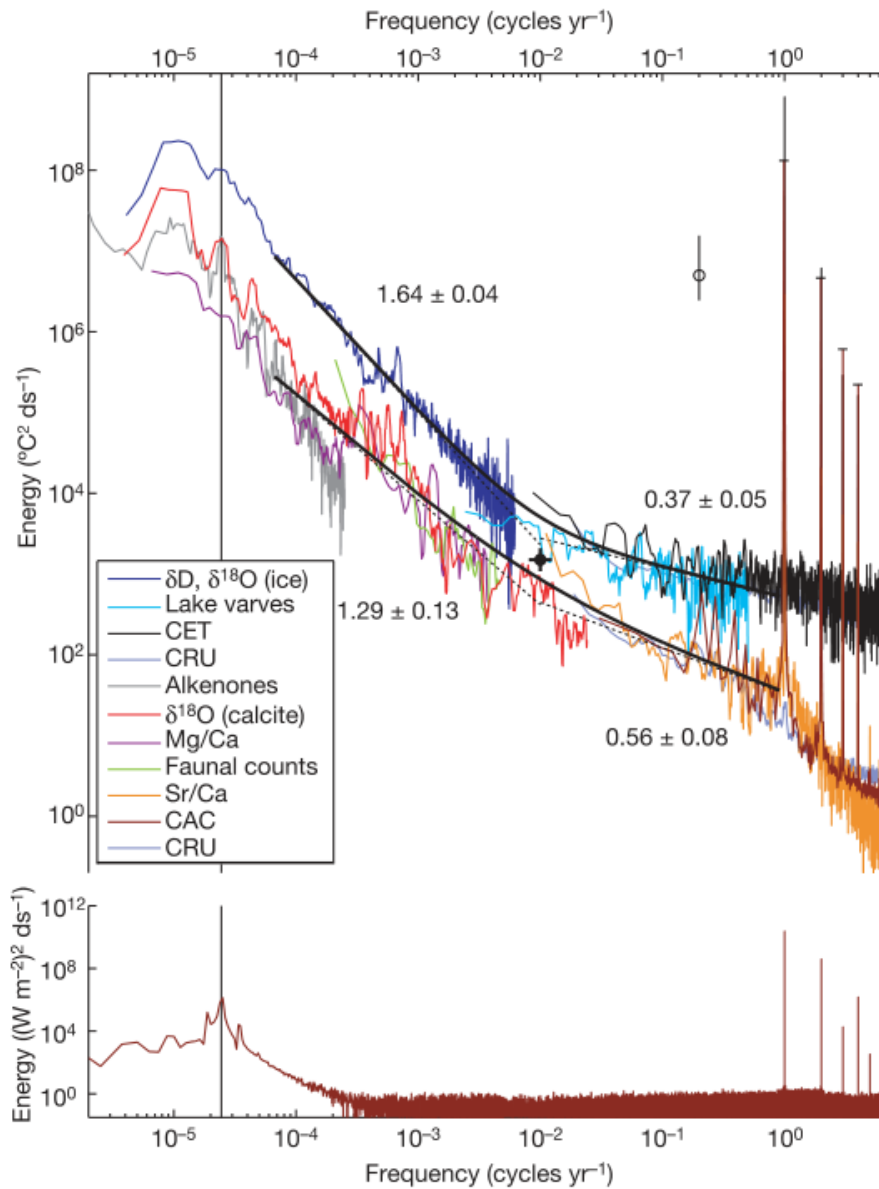
Sedimentation rate changes Or time-distortion



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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- ▶ 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

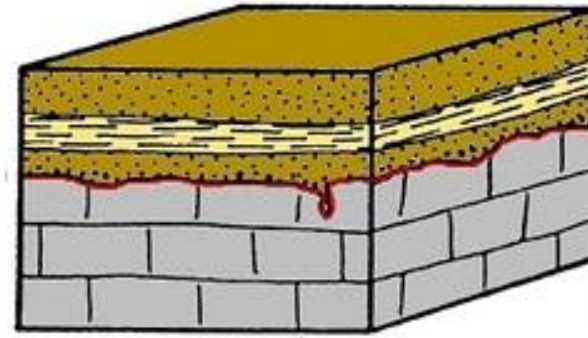
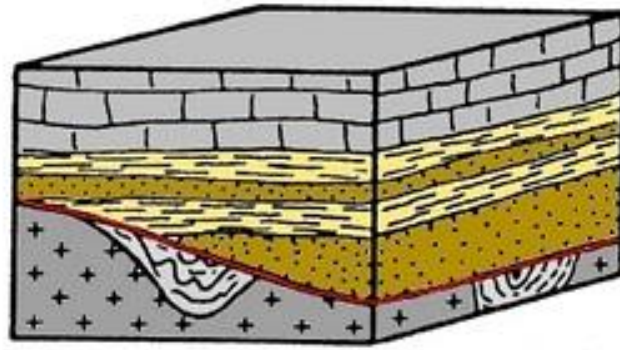
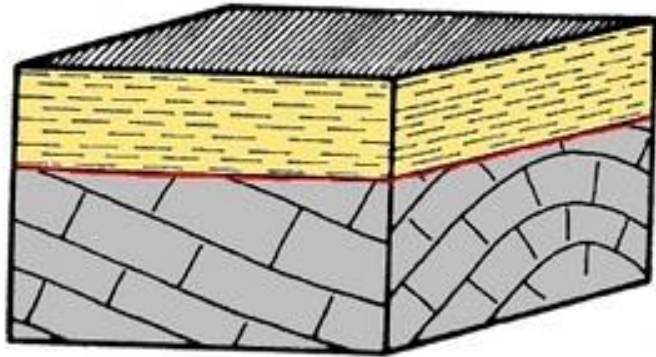


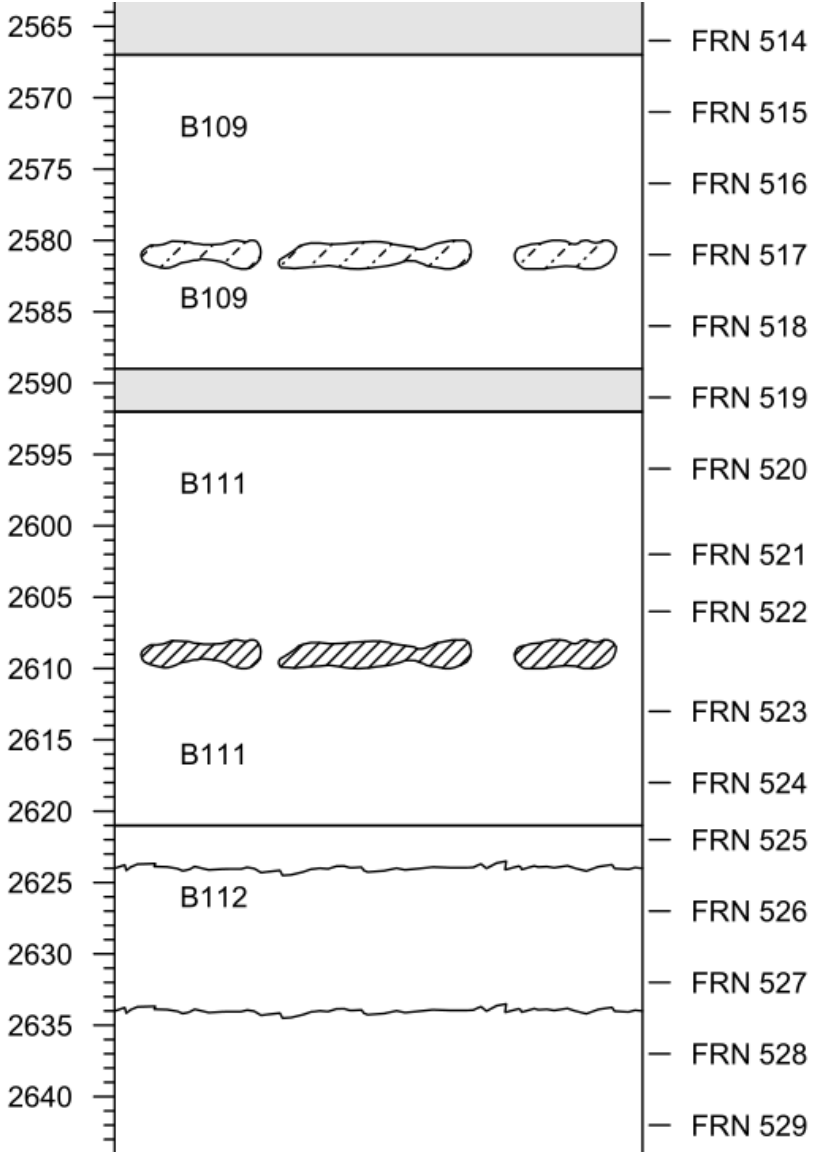
Image credit: Dr Jack Share

Faults



Photo credit: Miguel Vera León

Irregular sampling rate



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

Reliability of astronomical solutions

EON	ERA	PERIOD	EPOCH	Ma		
Phanerozoic	Cenozoic	Quaternary	Holocene		0.01	
			Pleistocene	Late	1.8	
		Early		2.6		
		Tertiary	Neogene	Pliocene		3.6
				Miocene	Late	5.3
					Middle	11.6
				Early	16.0	
			Paleogene	Oligocene		23.0
				Eocene	Late	28.4
					Early	30.9
				Paleocene	Late	37.2
		Early	48.6			
		Mesozoic	Cretaceous	Late		55.8
				Middle		61.7
	Early			65.5		
	Late			96.6		
	Middle			145.5		
	Early			161		
	Jurassic		Late		176	
			Middle		201.6	
			Early		216	
	Triassic		Late		235	
			Middle		245	
			Early		251.0	
	Paleozoic		Permian		260	
			Carboniferous		271	
			Pennsylvanian		299.0	
			Mississippian		318	
			Devonian		359	
			Silurian		385	
			Ordovician		416	
		Cambrian		423		
		Cambrian		436		
Cambrian		444				
Precambrian	Proterozoic	Late Neoproterozoic		461		
		Middle Mesoproterozoic		472		
		Early Paleoproterozoic		488		
	Archean	Neoarchean		501		
		Mesoarchean		510		
		Paleoarchean		510		
		Eoarchean		521		
		Haydean		542		
		Haydean		3600		
		Haydean		3850		

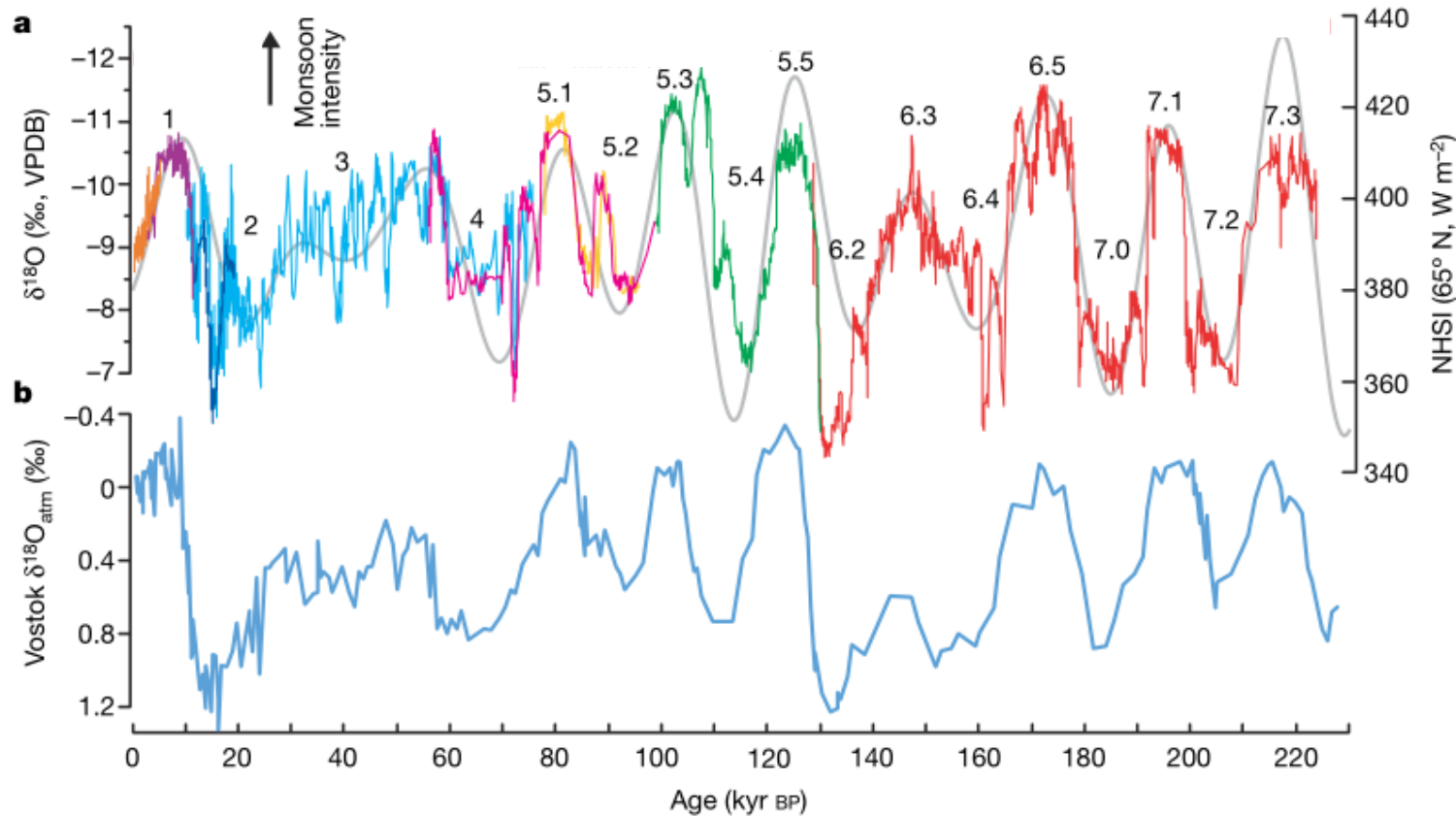
- ▶ Up to **10 Ma**: precession and obliquity solutions (loss due to dissipative effects, tides, etc.)
- ▶ Up to **50 Ma**: precise orbits, eccentricity cycles (loss due to deterministic chaotic behaviour)

- ▶ 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)



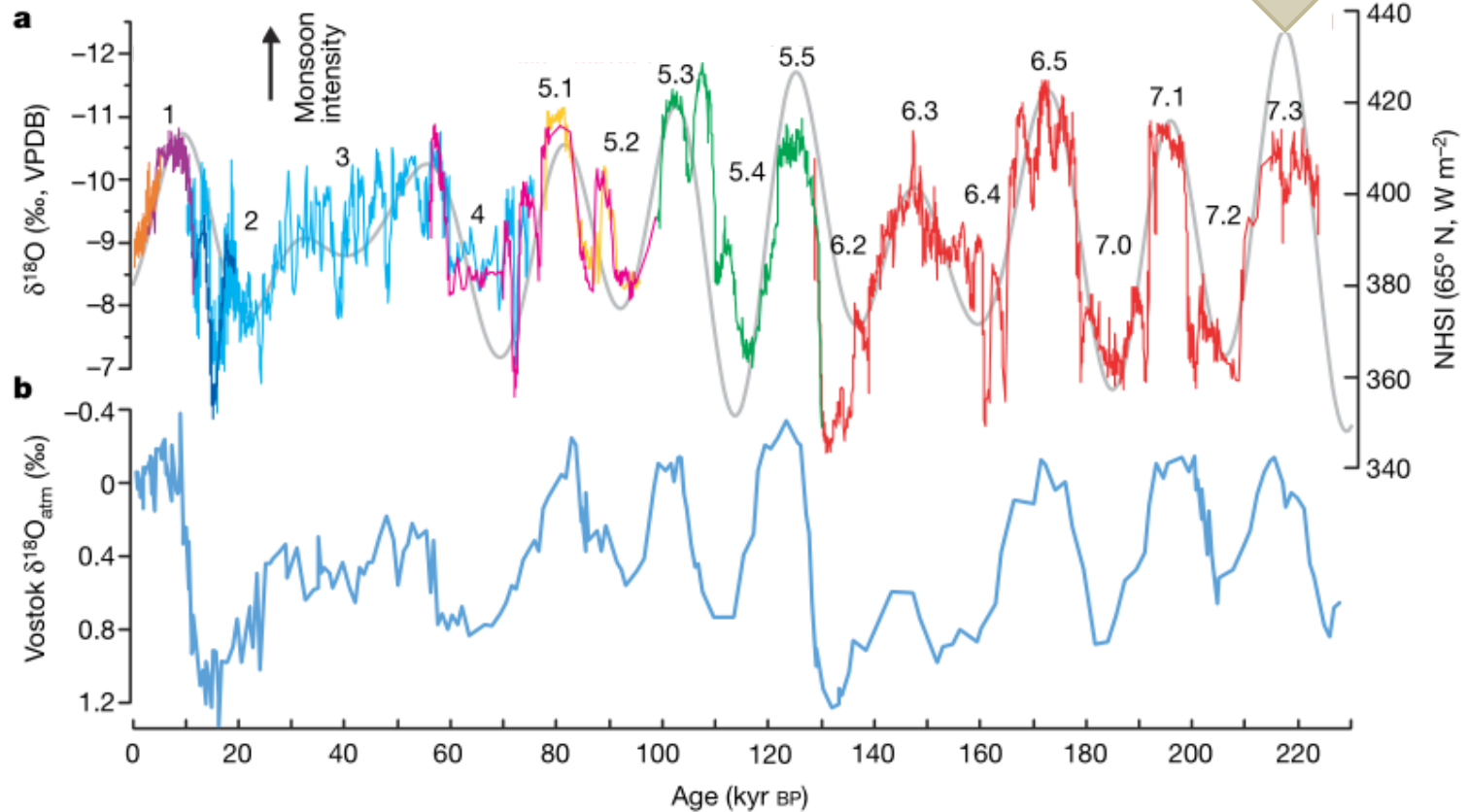
Wang et al.,
2008

Figure 1 | Comparison of Sanbao/Hulu $\delta^{18}\text{O}$ records with NHSI and atmospheric $\delta^{18}\text{O}$ record over the past 224 kyr BP. **a**, Time versus Sanbao $\delta^{18}\text{O}$ 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° N¹⁰ (grey).

For comparison, the Hulu $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ record from Vostok ice core, Antarctica²⁸.

Astronomical solutions (when we have them)

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

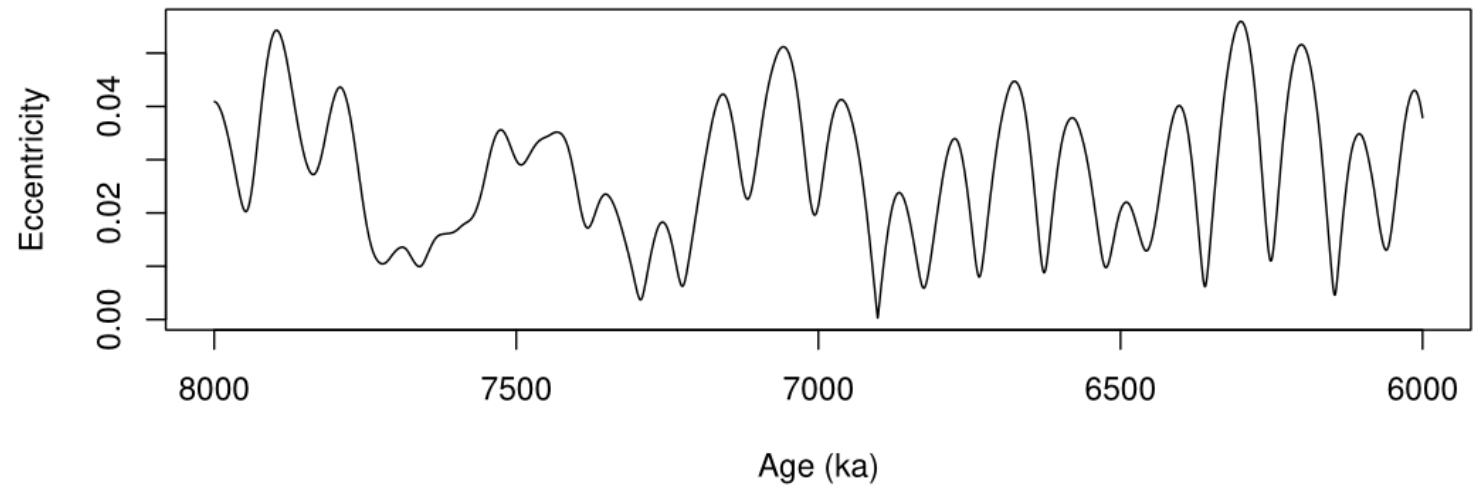
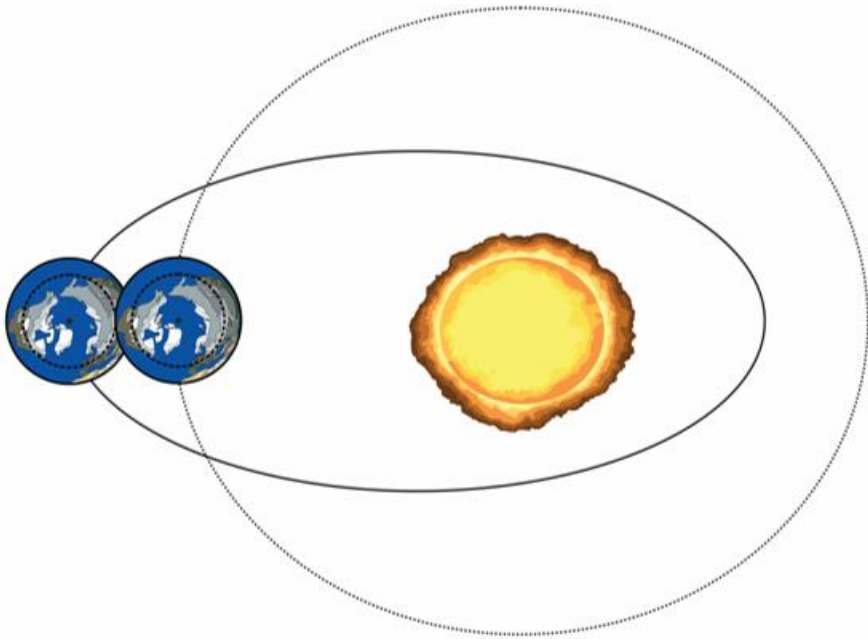
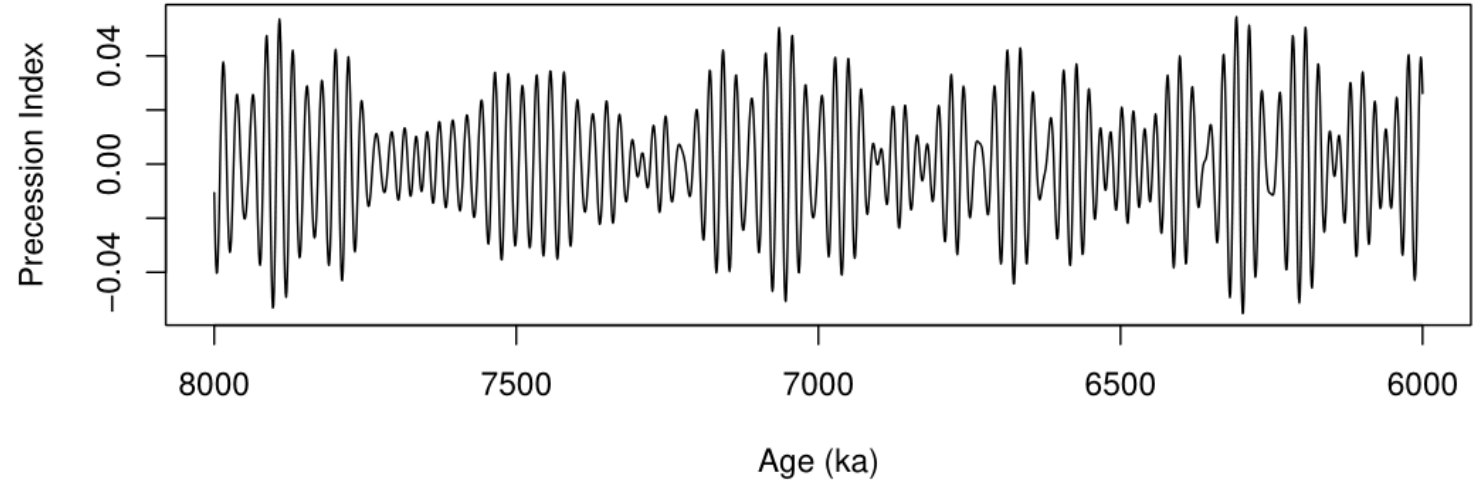
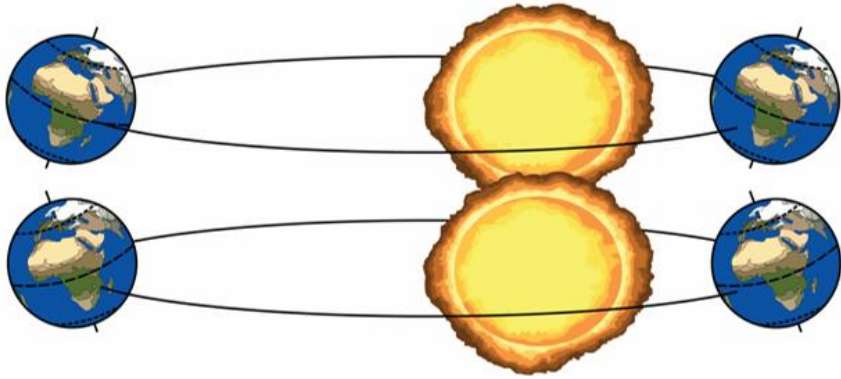


Wang et al.,
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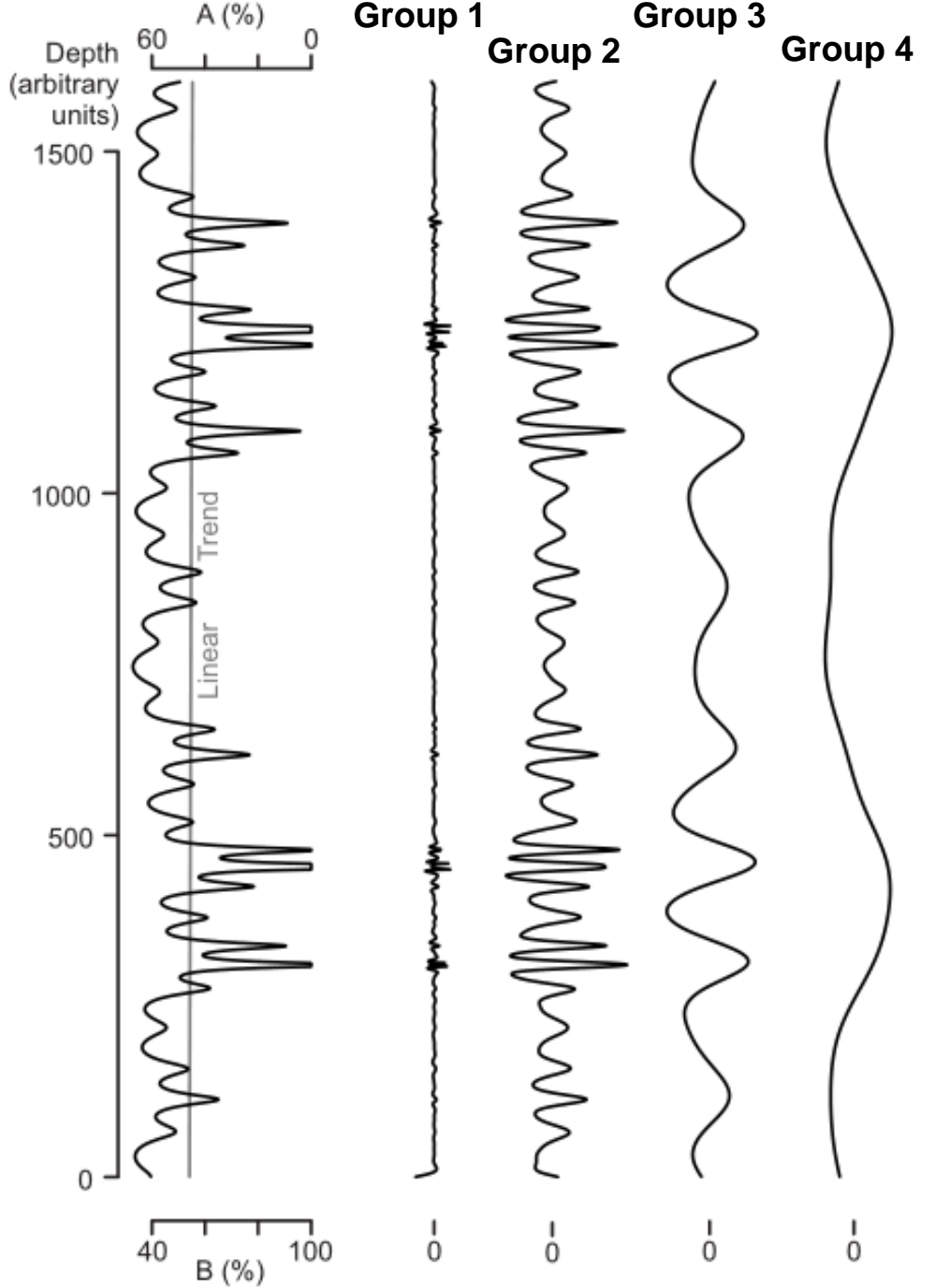
Amplitude modulations



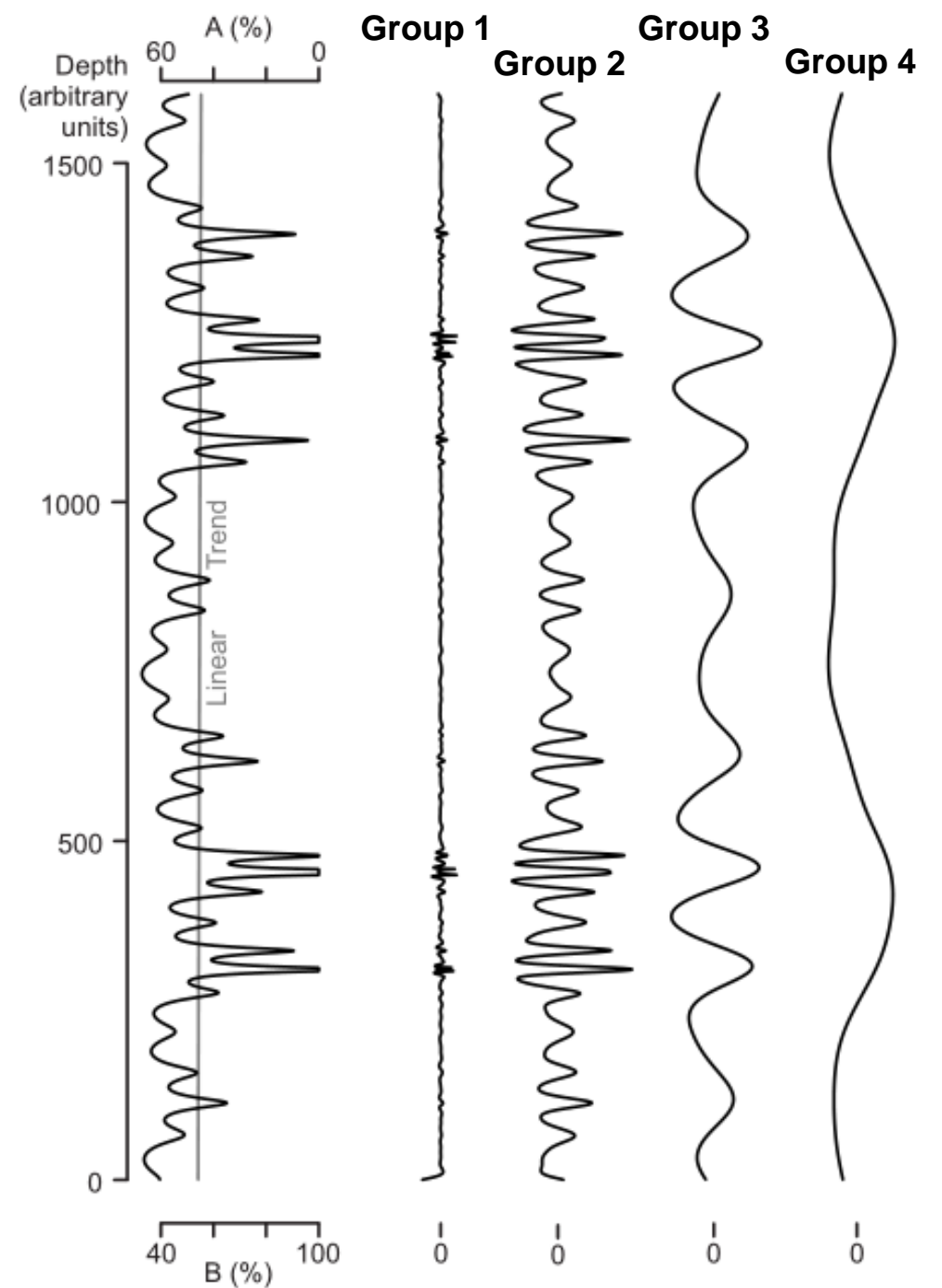
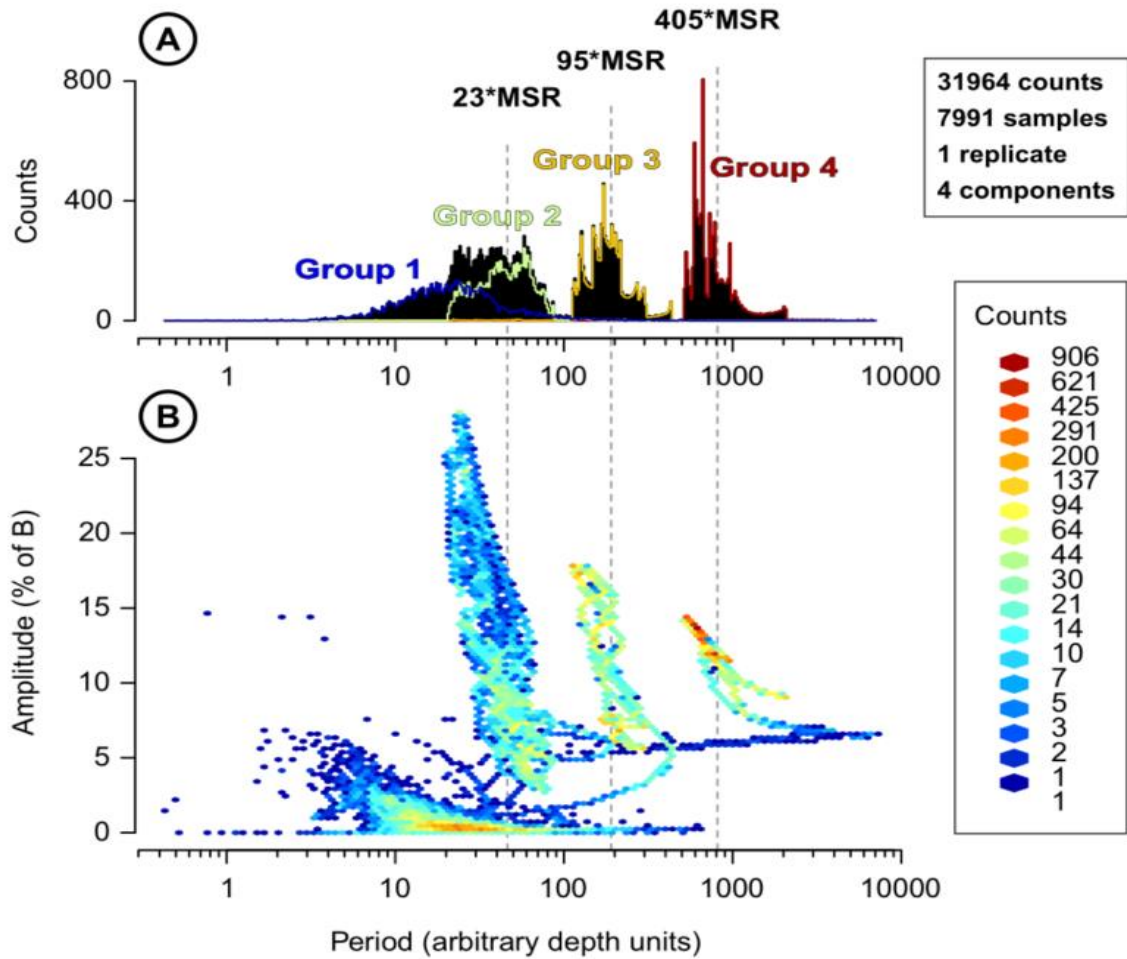
Ratios of frequencies



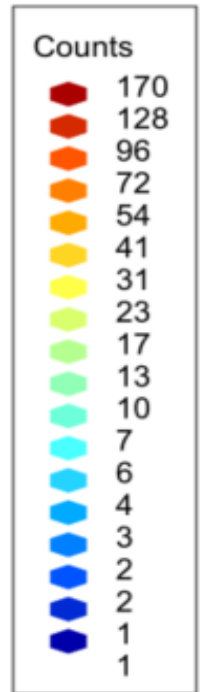
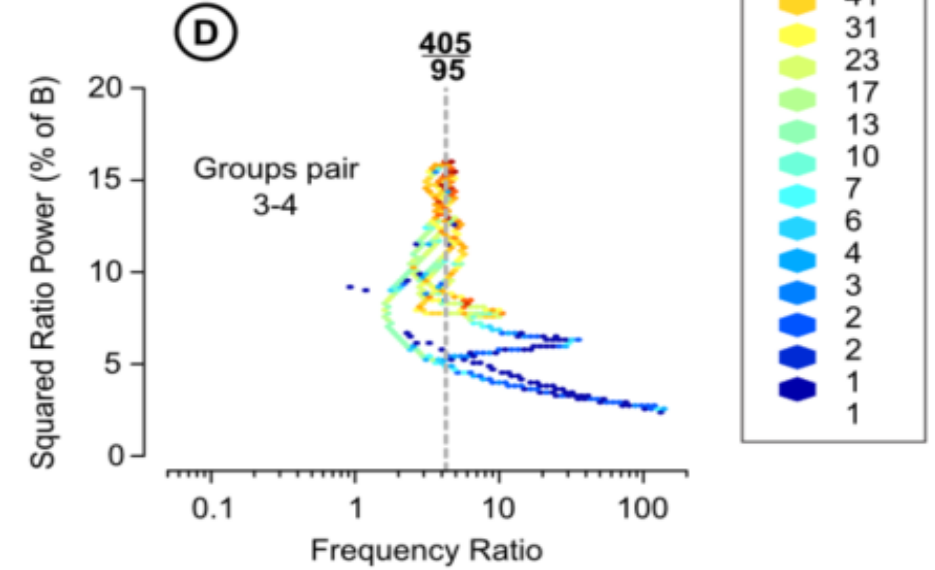
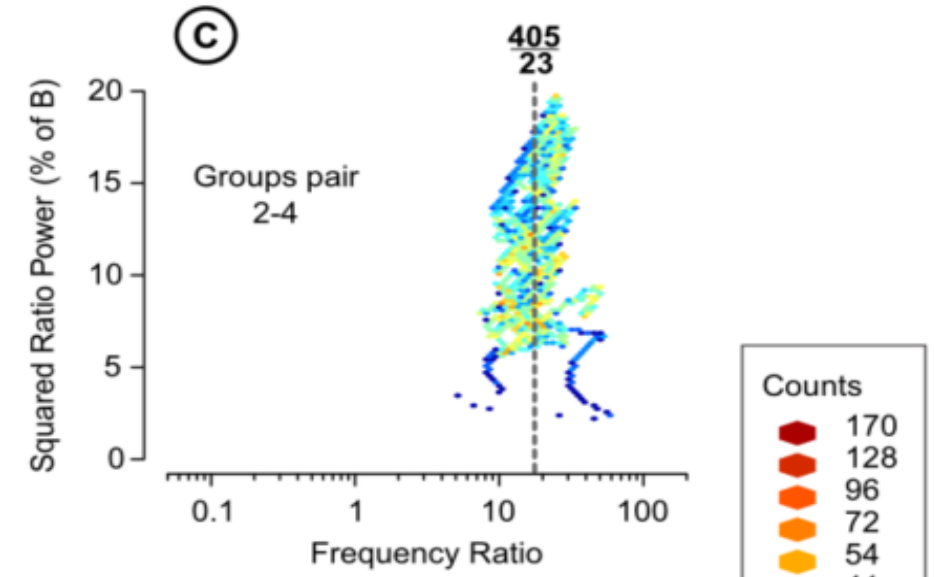
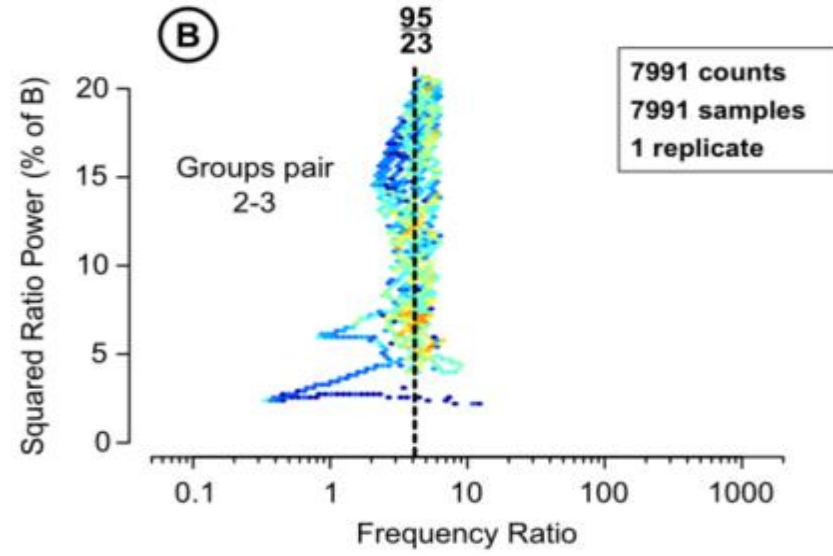
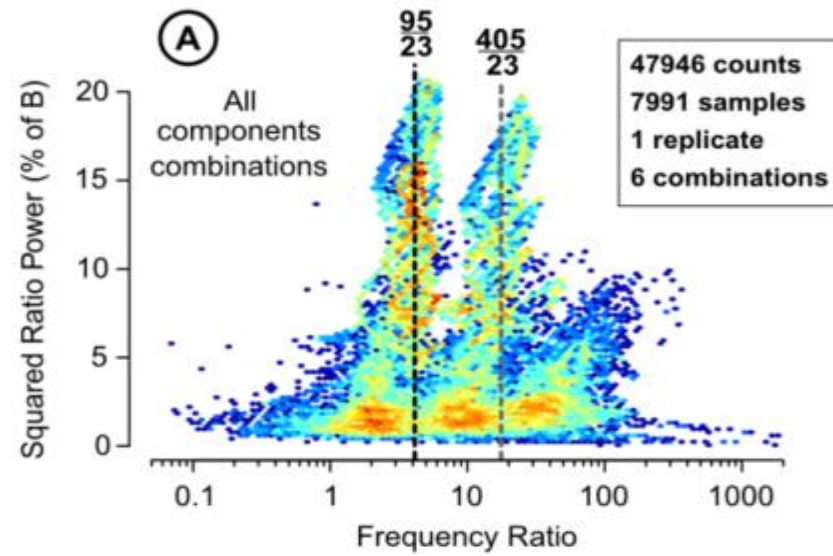
Ratios of frequencies



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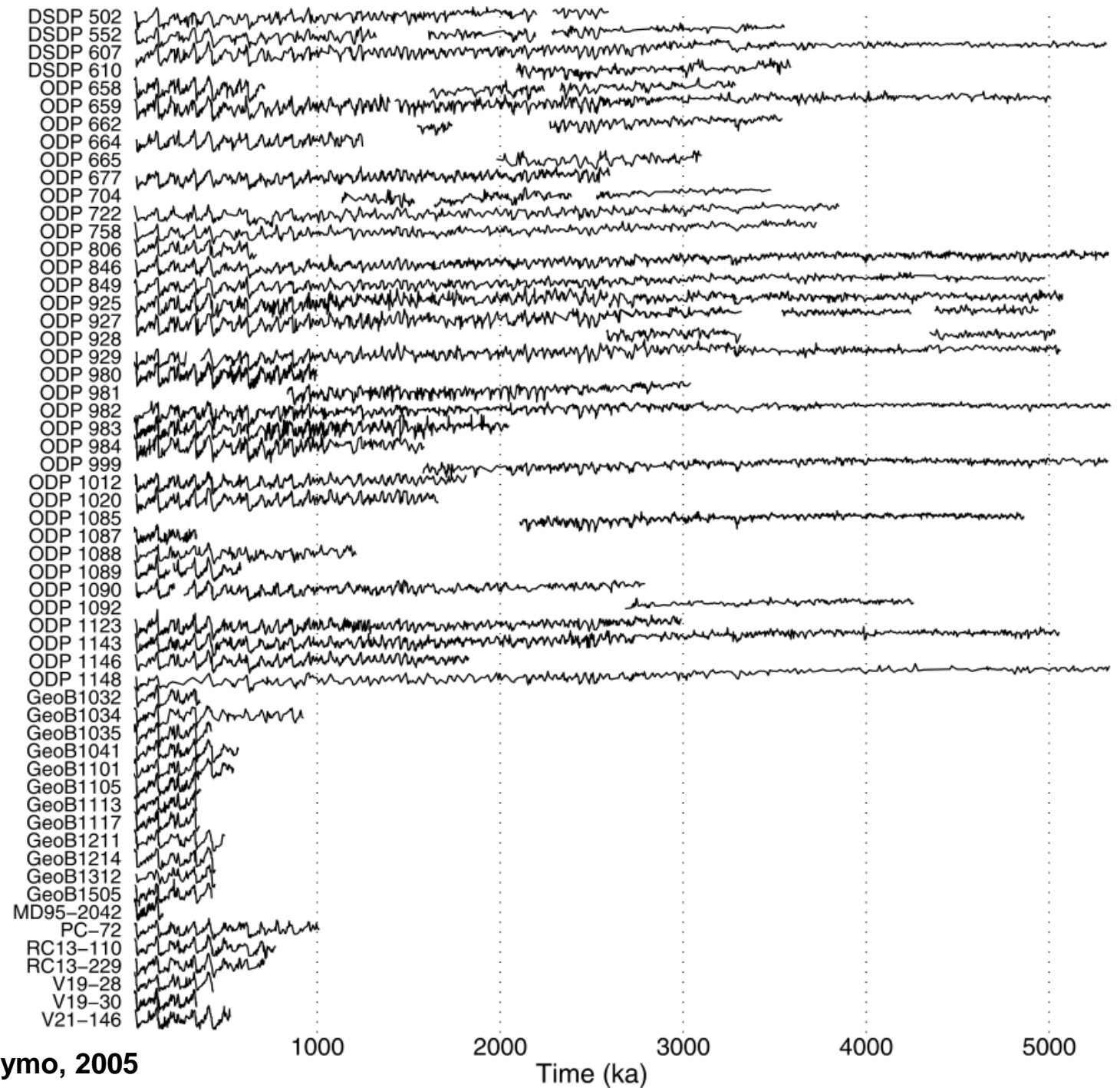


Ratios of frequencies



Other geological records

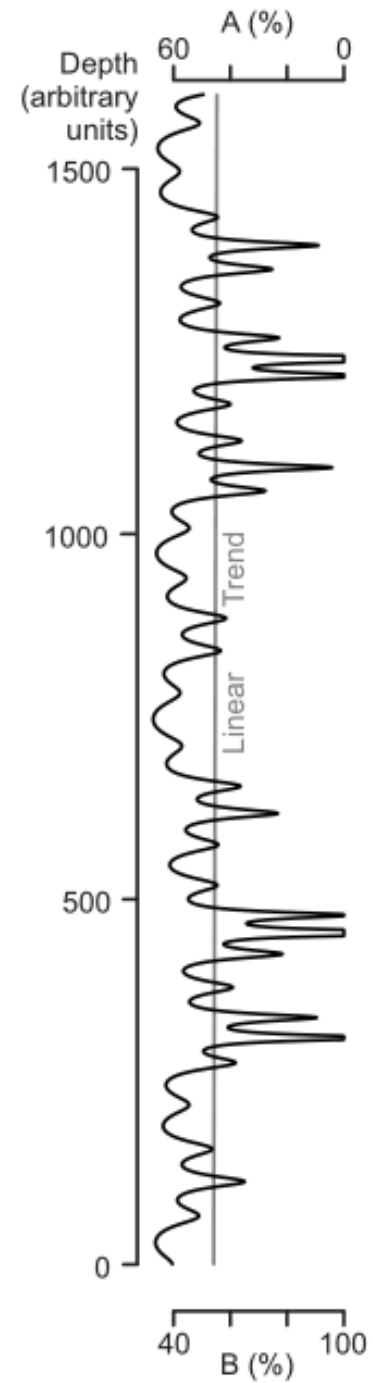
- ▶ The geological record should be coherent throughout the world for similar time periods



Disentangling the signal

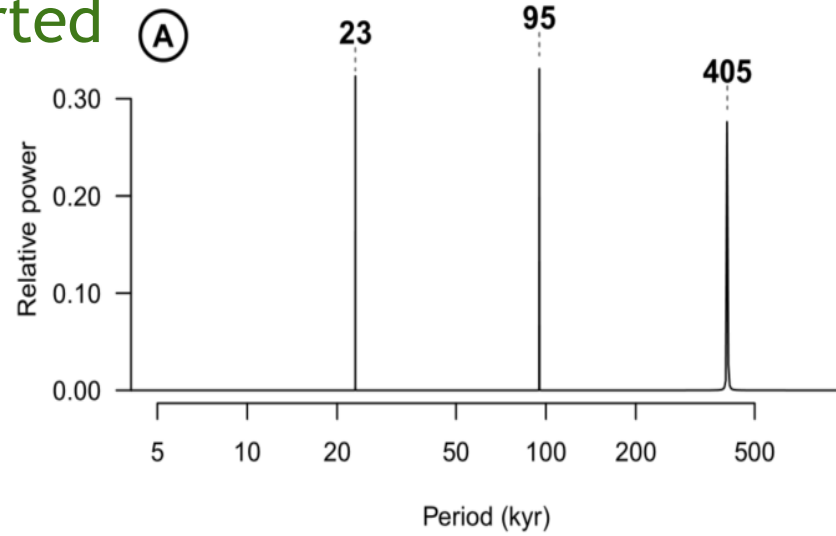
The background features a series of overlapping, semi-transparent green triangles and polygons in various shades, ranging from light lime green to dark forest green. These shapes are primarily located on the right side of the slide, creating a dynamic, layered effect. The text 'Disentangling the signal' is positioned on the left side of the slide, centered vertically.

Fourier spectra

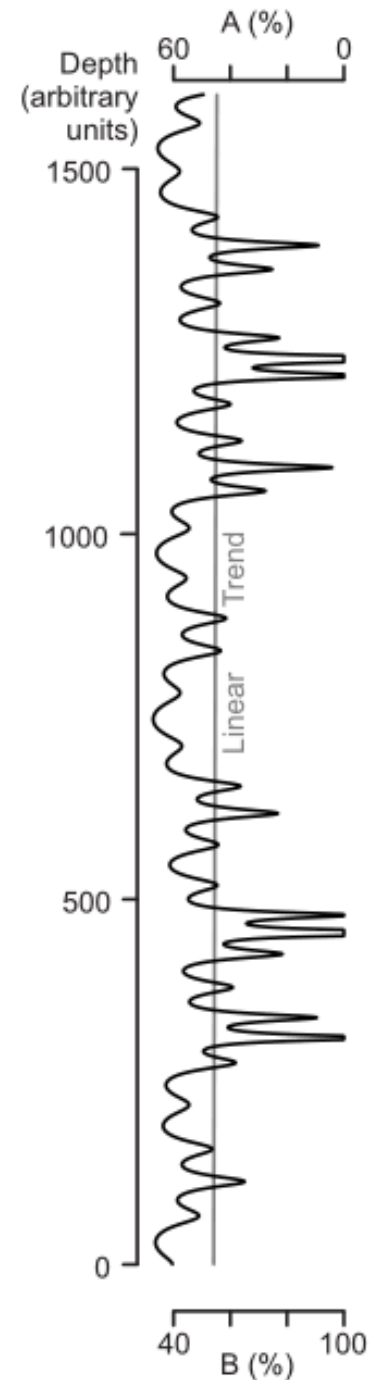
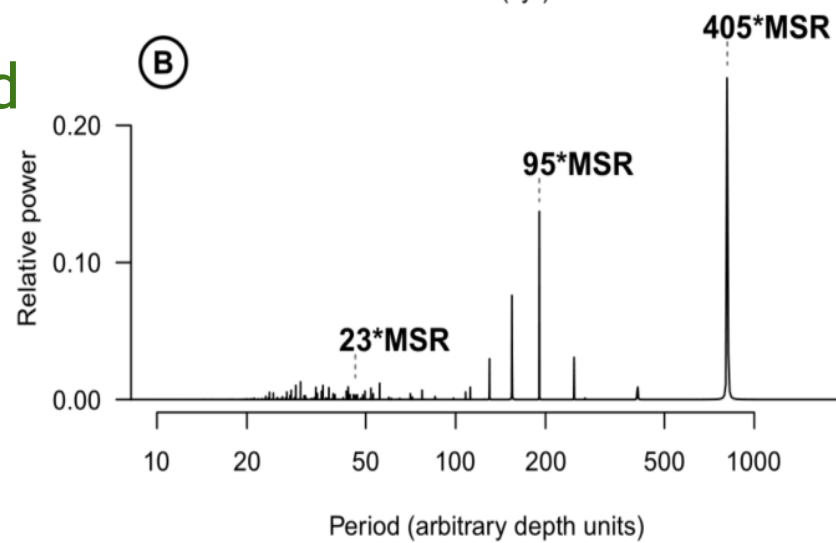


Fourier spectra

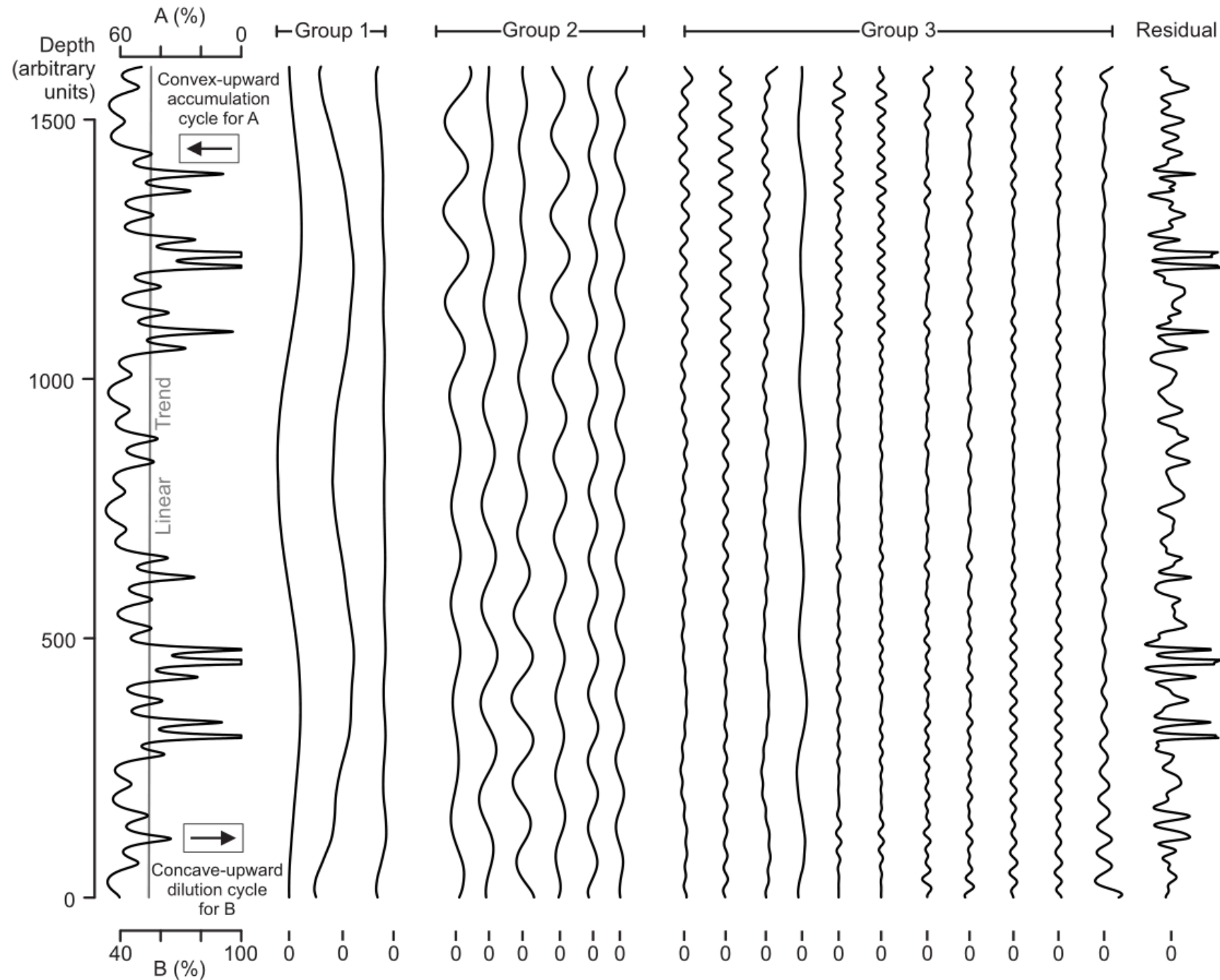
Undistorted



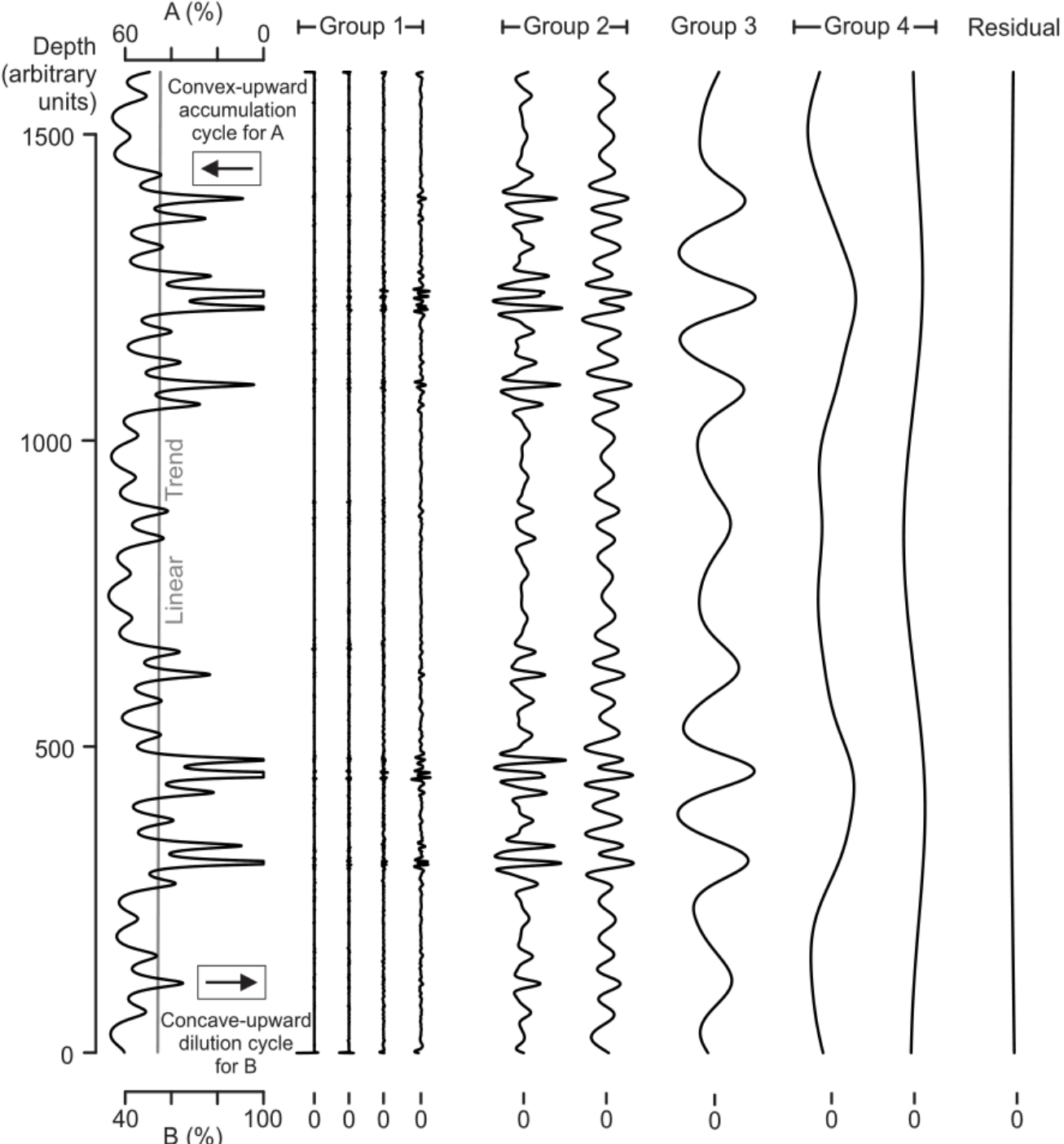
Depth-distorted



Singular Spectrum Analysis (SSA)



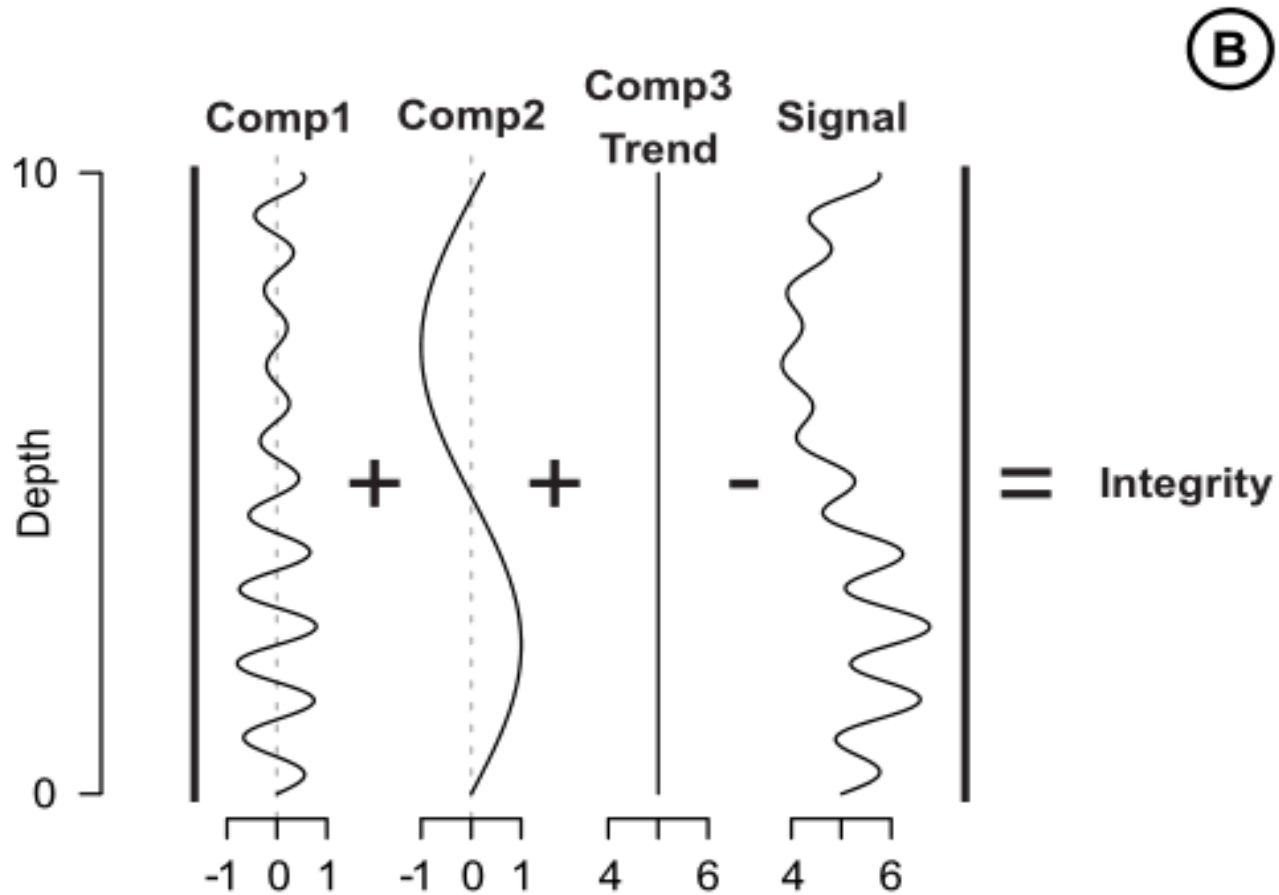
Ensemble Empirical Mode Decomposition (EEMD)



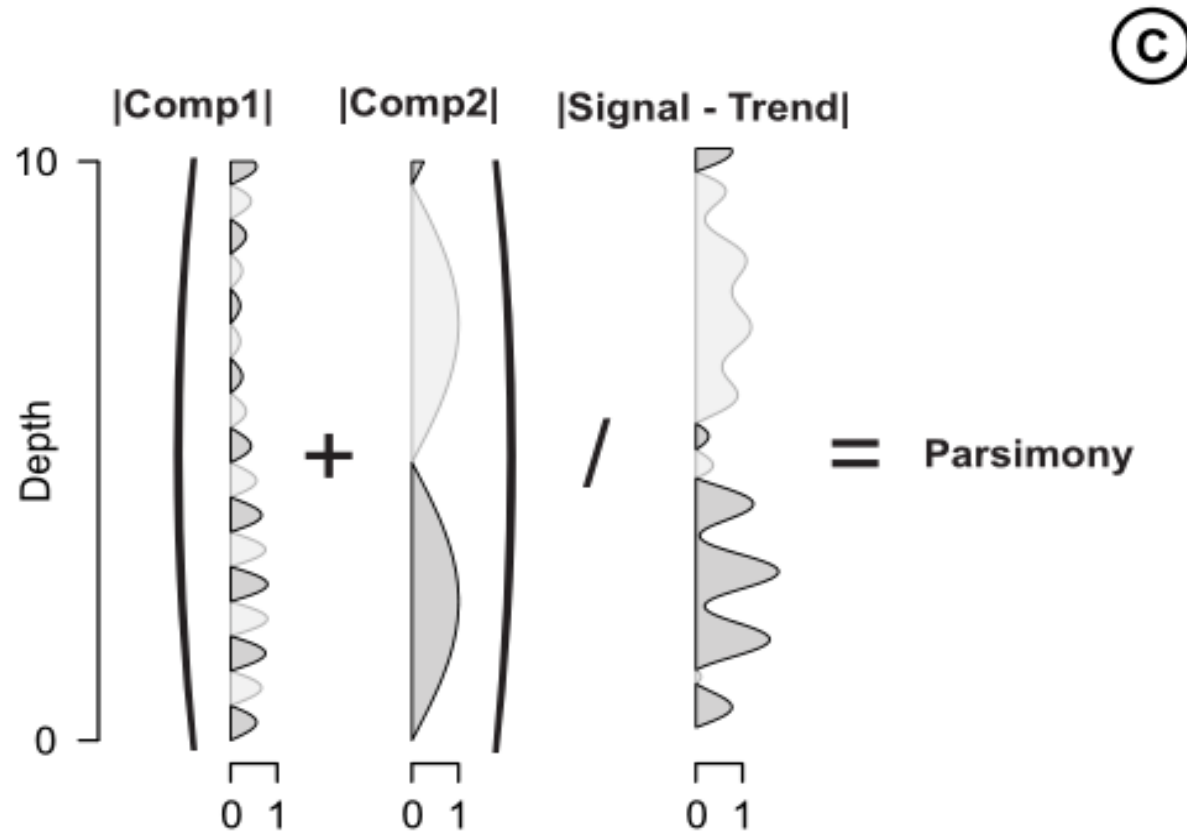
The background features abstract, overlapping geometric shapes in various shades of green, ranging from light lime to dark forest green. The shapes are primarily triangles and polygons, creating a dynamic, layered effect. The overall composition is clean and modern, with the text centered on the white space.

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

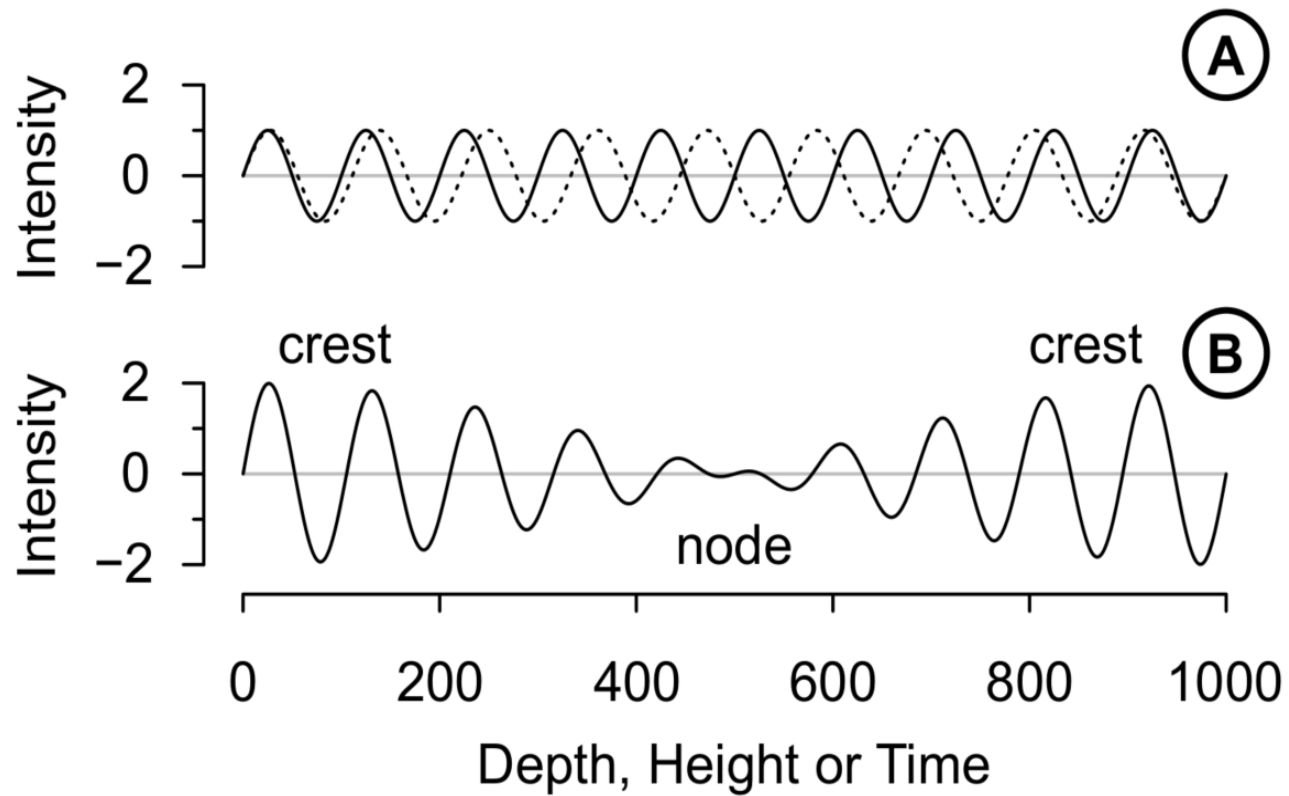
Ability to quantify the loss of information

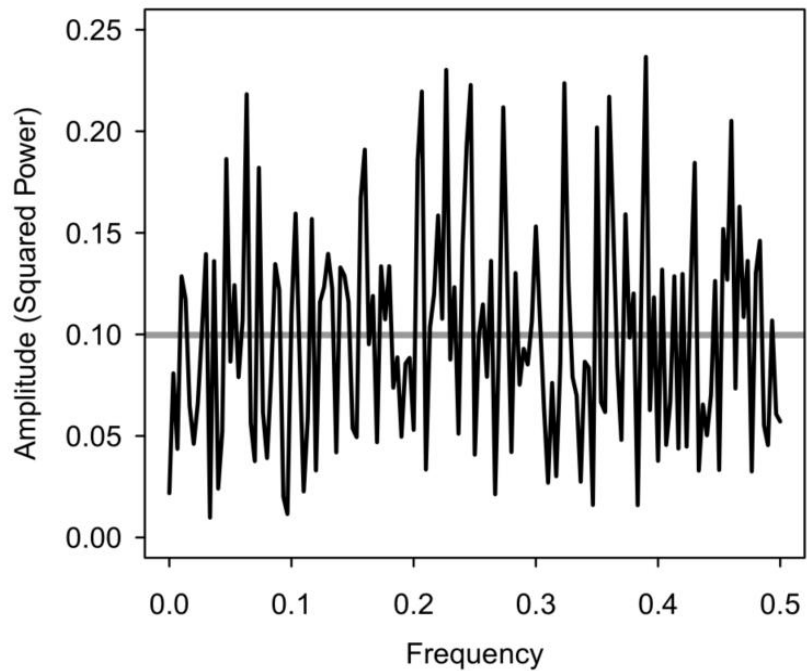


Ability to quantify the addition of spurious information

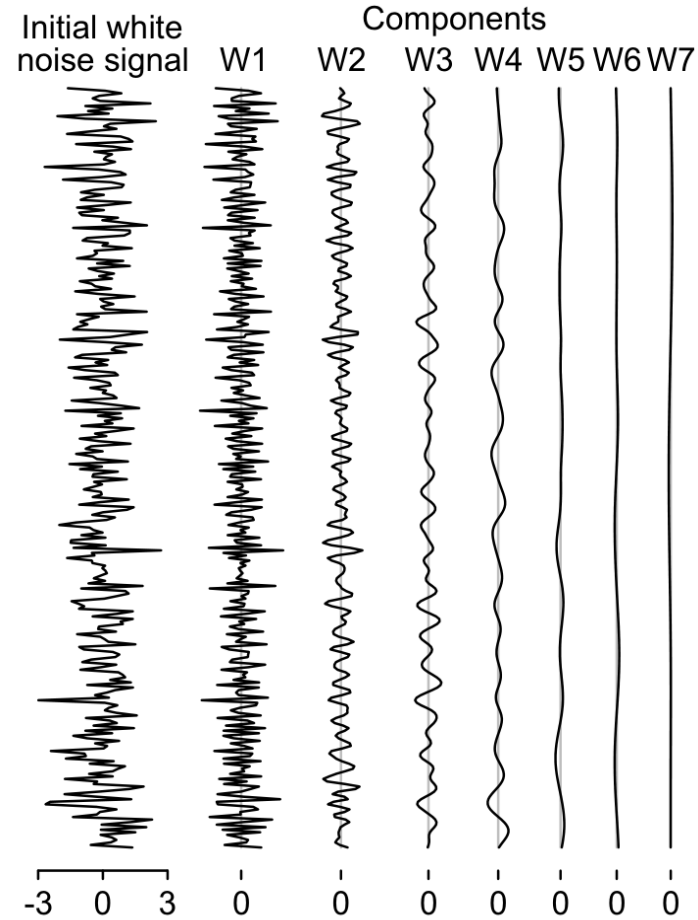
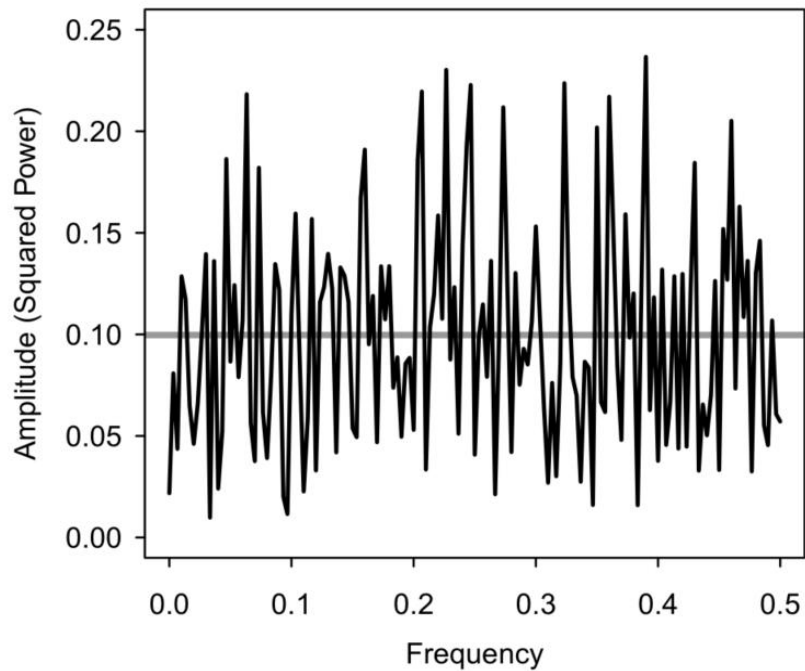


Ability to quantify the addition of spurious information





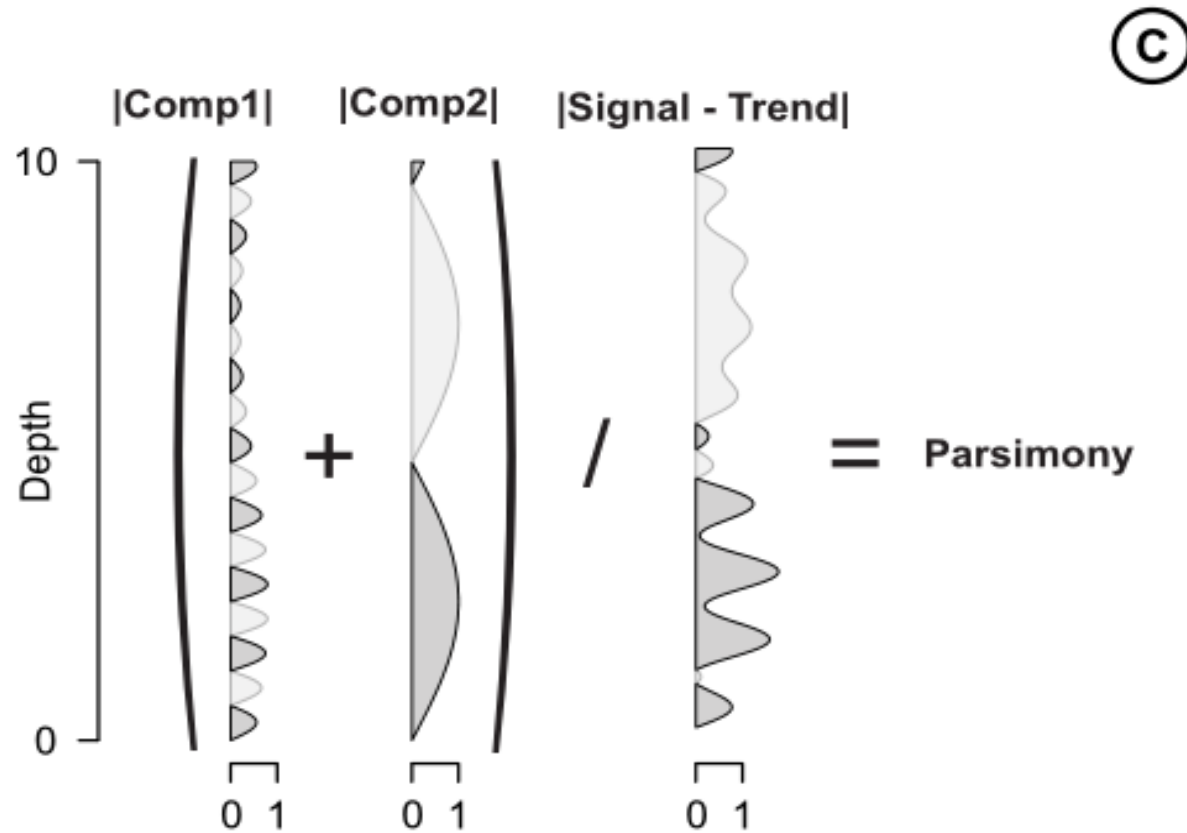
- ▶ Power spectra of a 300 points white noise signal.
- ▶ Parsimony: 12.26 (IN TIME DOMAIN OF A FOURIER **SERIES**)
- ▶ 1126 % absolute intensity in the decomposition in excess compared to the original signal



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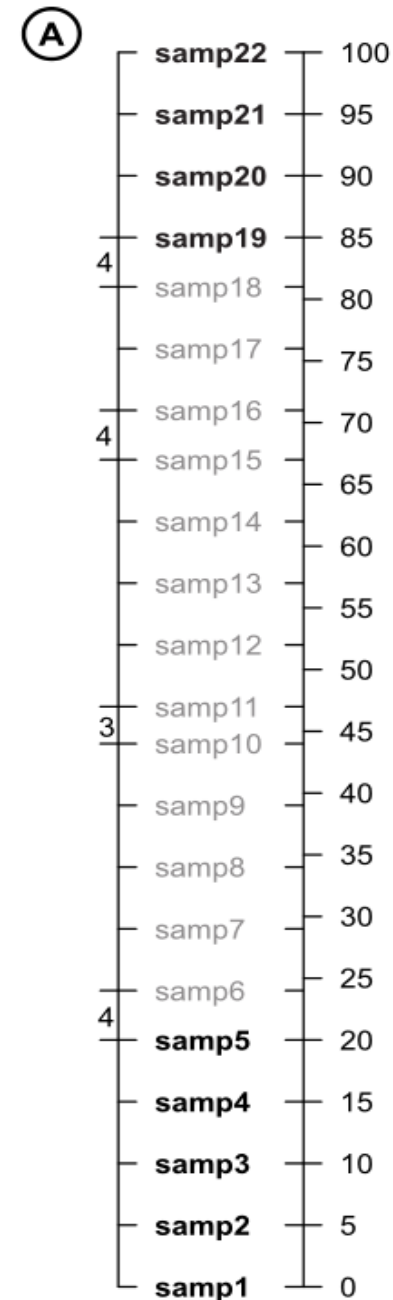
- ▶ EEMD decomposition of the same 300 points white noise signal.
- ▶ Parsimony: 1.74
- ▶ 74% excess absolute intensity

Ability to quantify the addition of spurious information

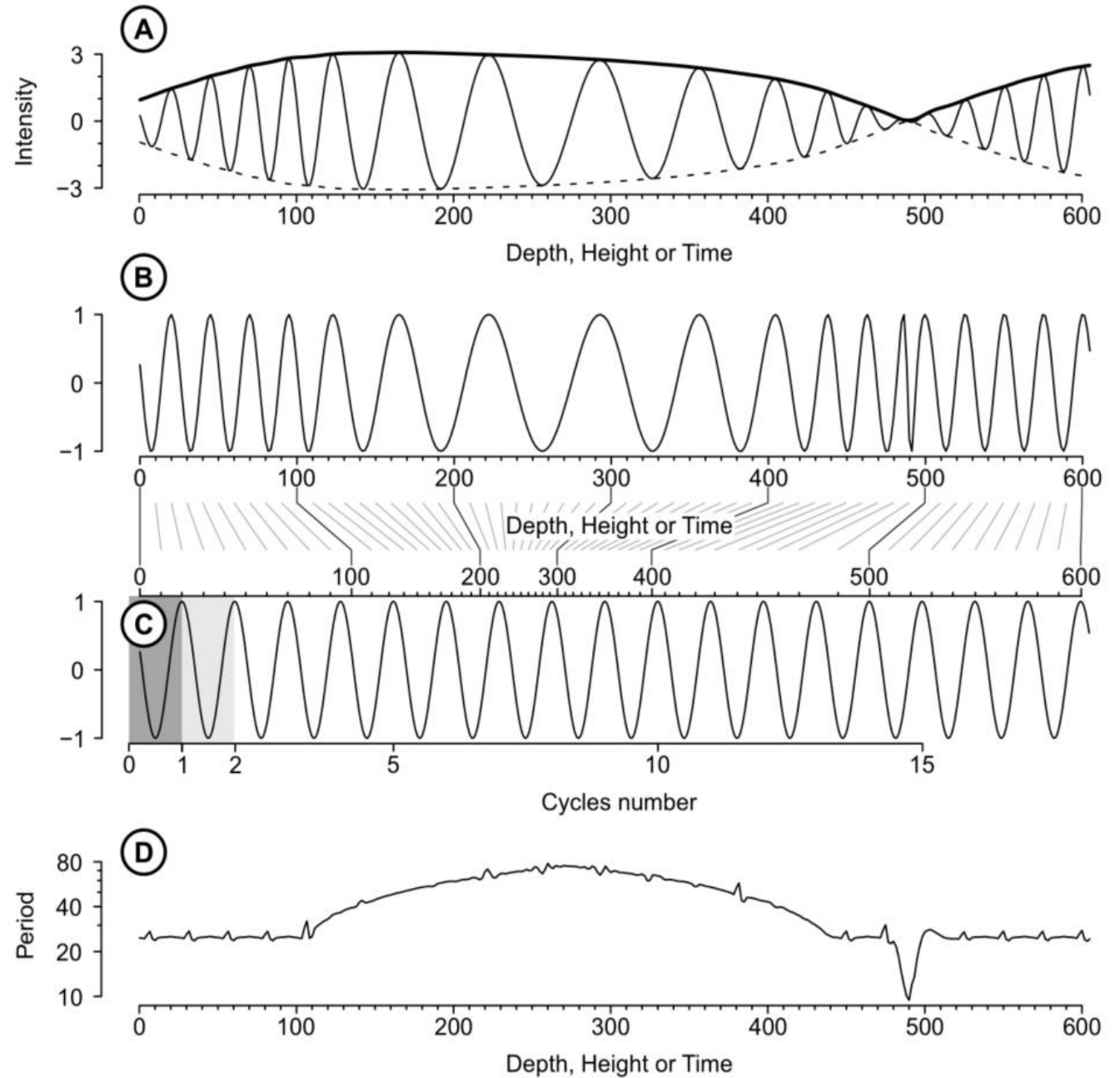


Ability to check whether the information was not changed (especially the position of samples)

- ▶ `divisor()`, in StratigrapherR 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

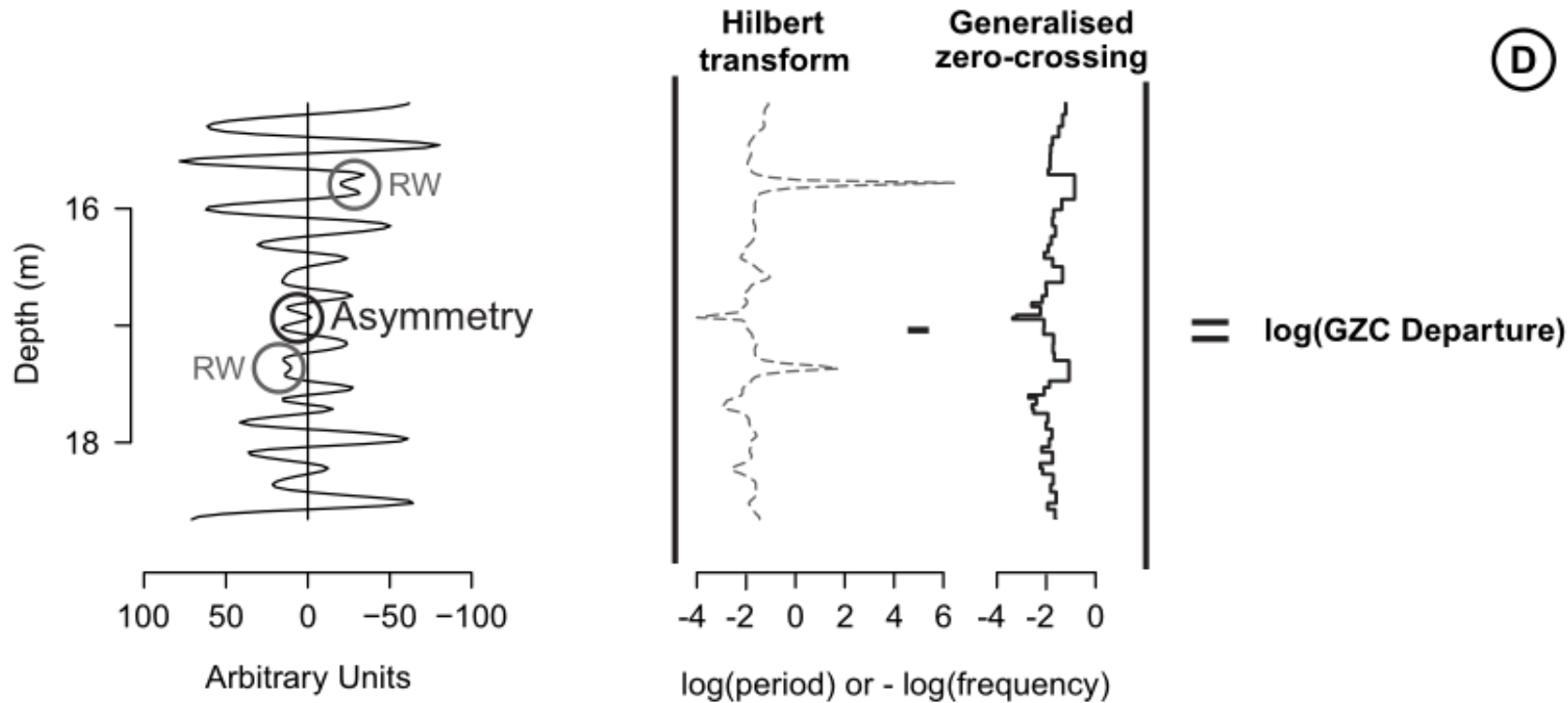


Ability to extract the instantaneous frequency



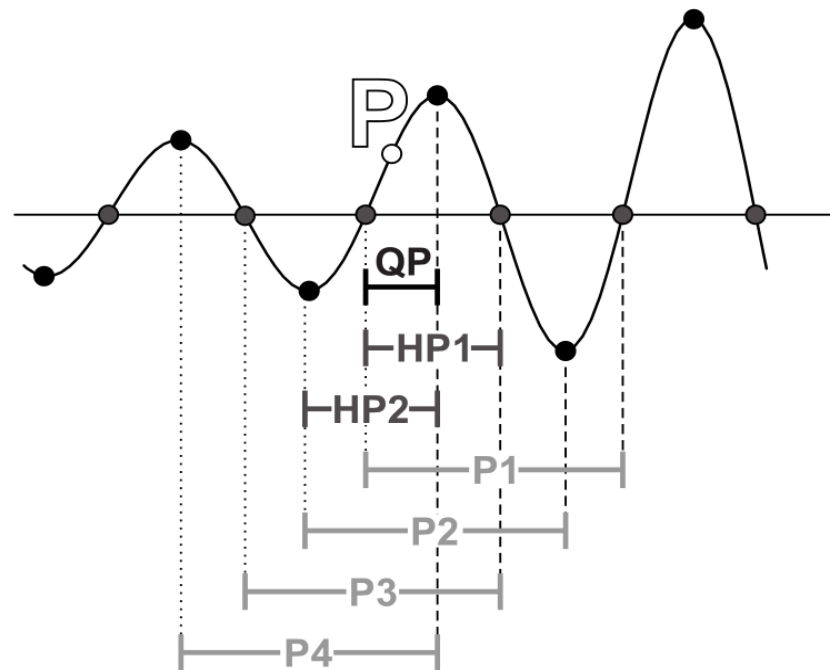
Ability to provide an error on the instantaneous frequency

- ▶ Generalised Zero-Crossing Departure



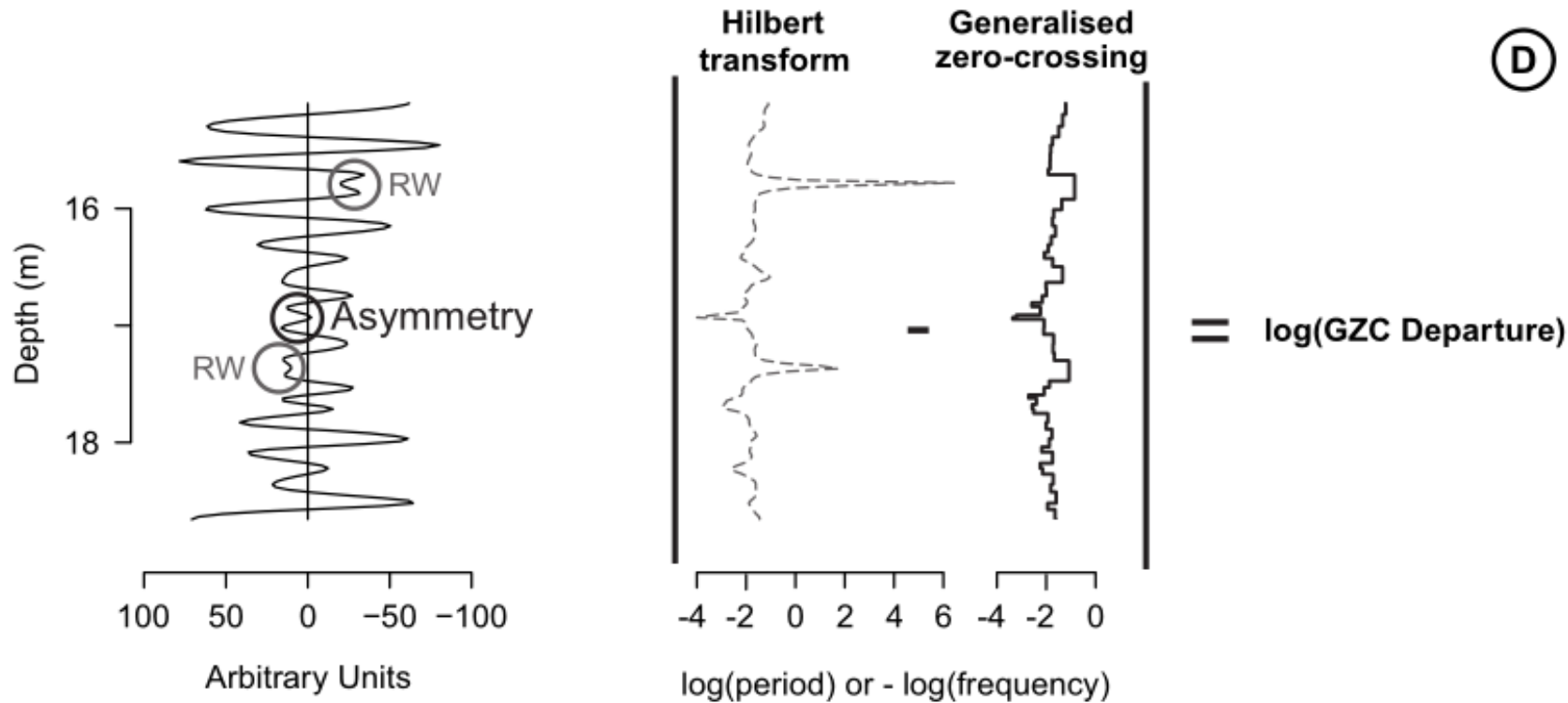
Ability to provide an error on the instantaneous frequency

- Generalised Zero-Crossing



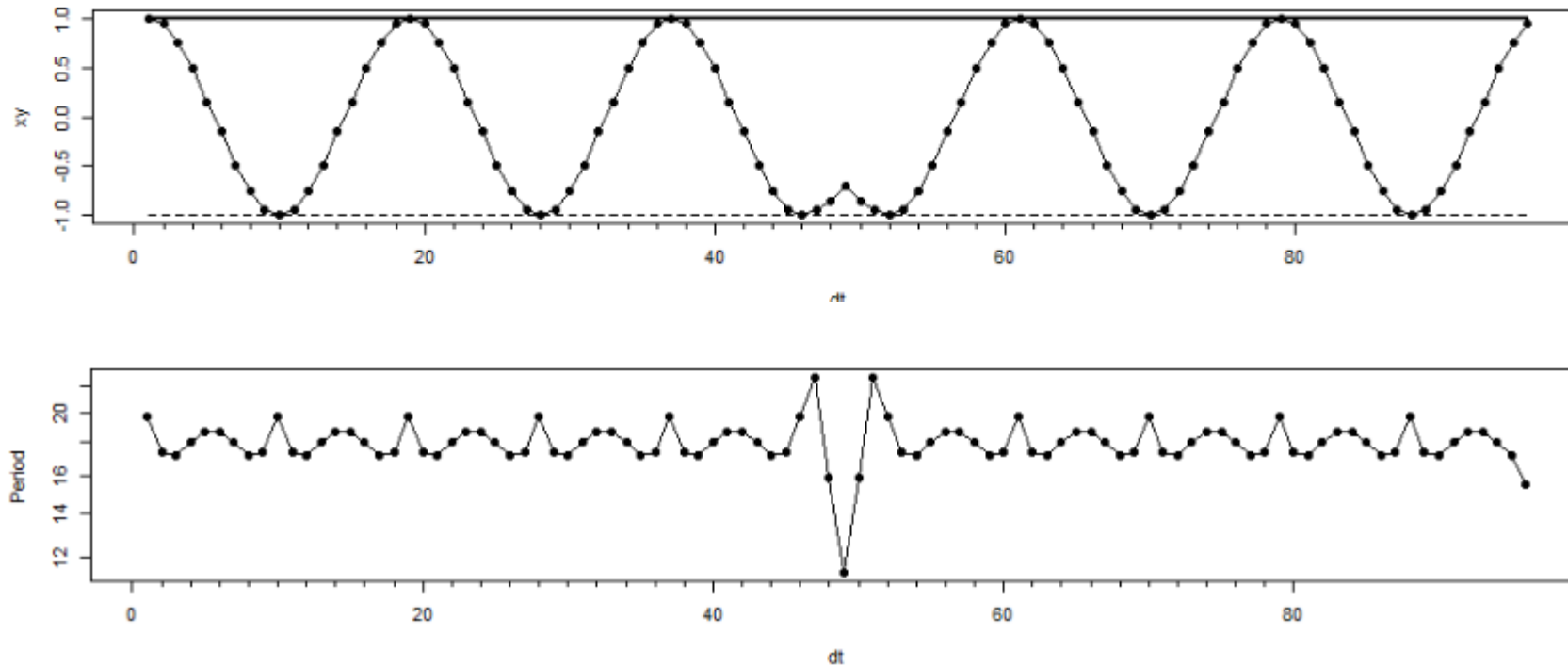
Ability to provide an error on the instantaneous frequency

- Generalised Zero-Crossing Departure



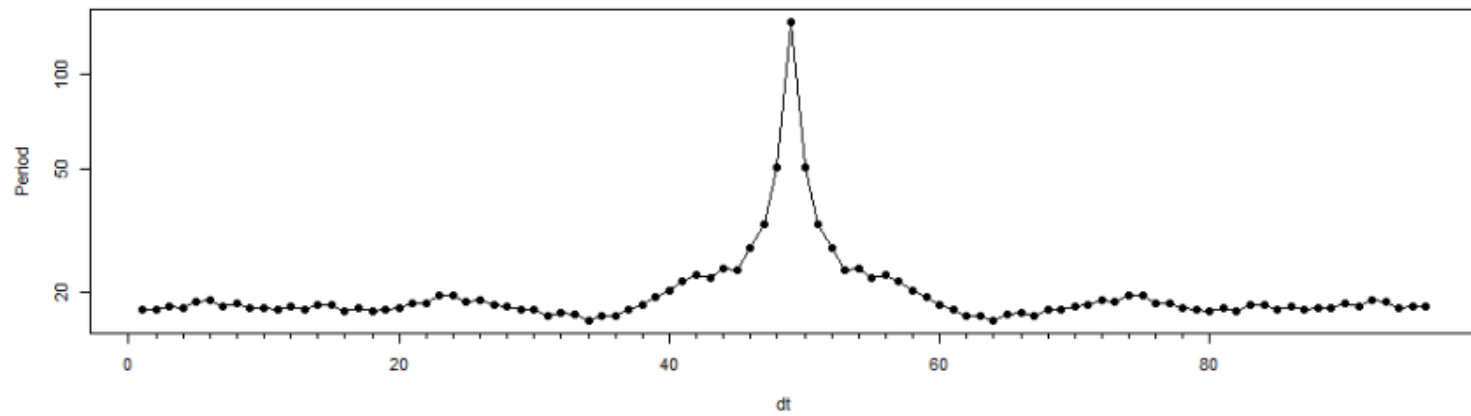
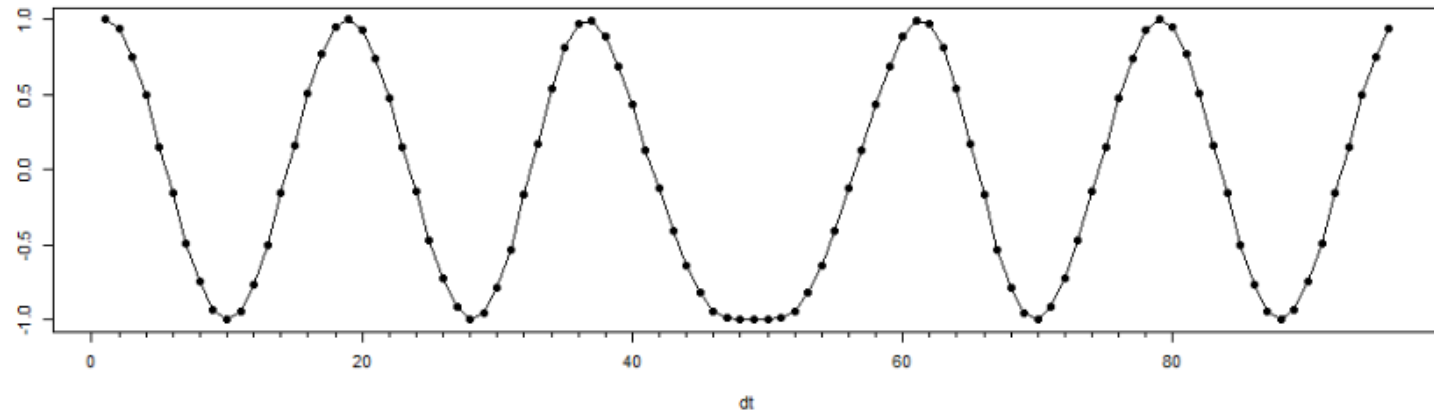
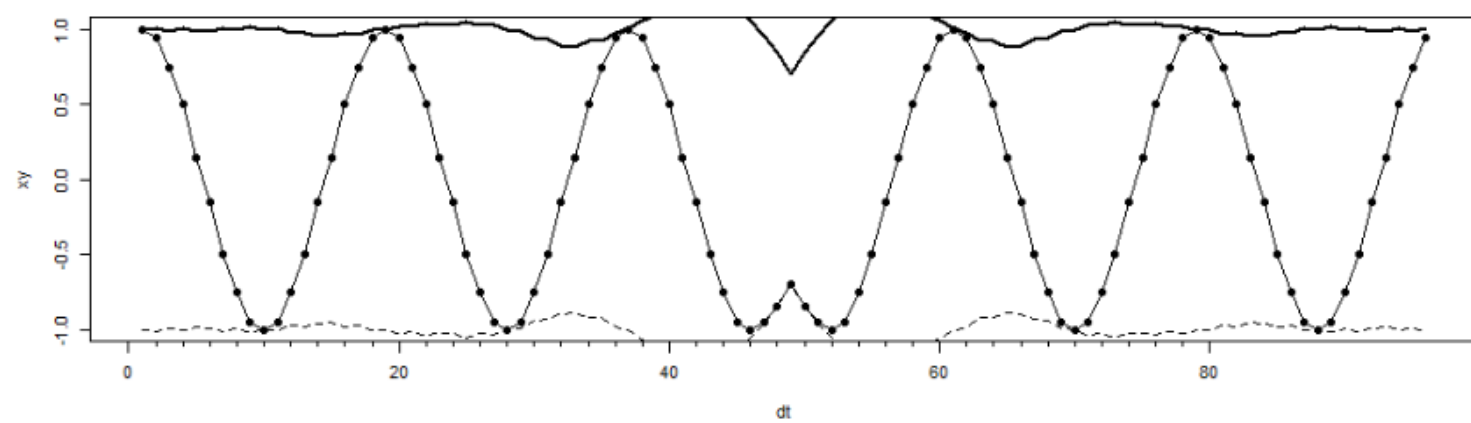
Ability to provide an error on the instantaneous frequency

Riding wave on direct quadrature instantaneous frequency estimation



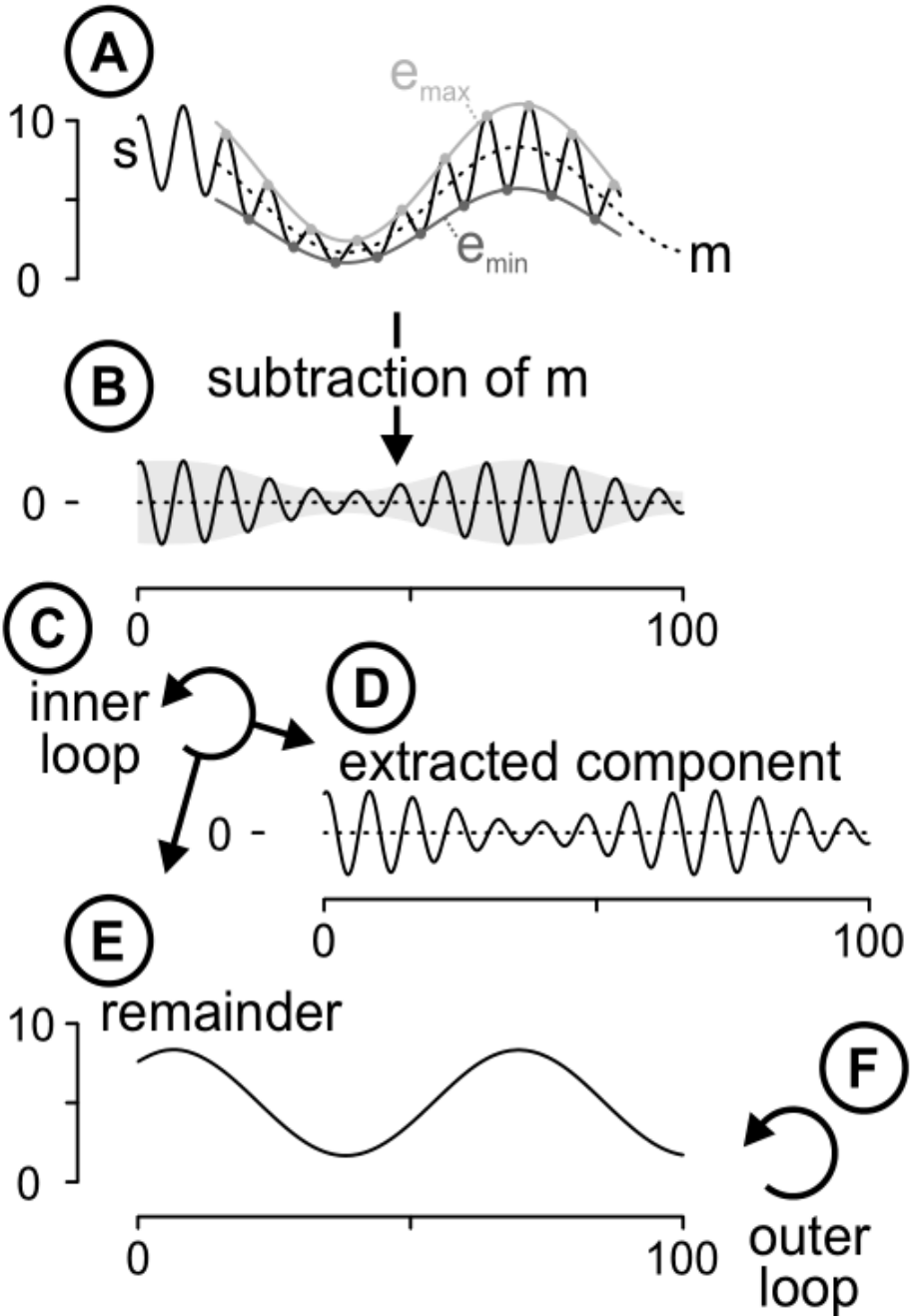
Ability to provide an error on the instantaneous frequency

Riding wave on Hilbert transform-based instantaneous frequency estimation



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

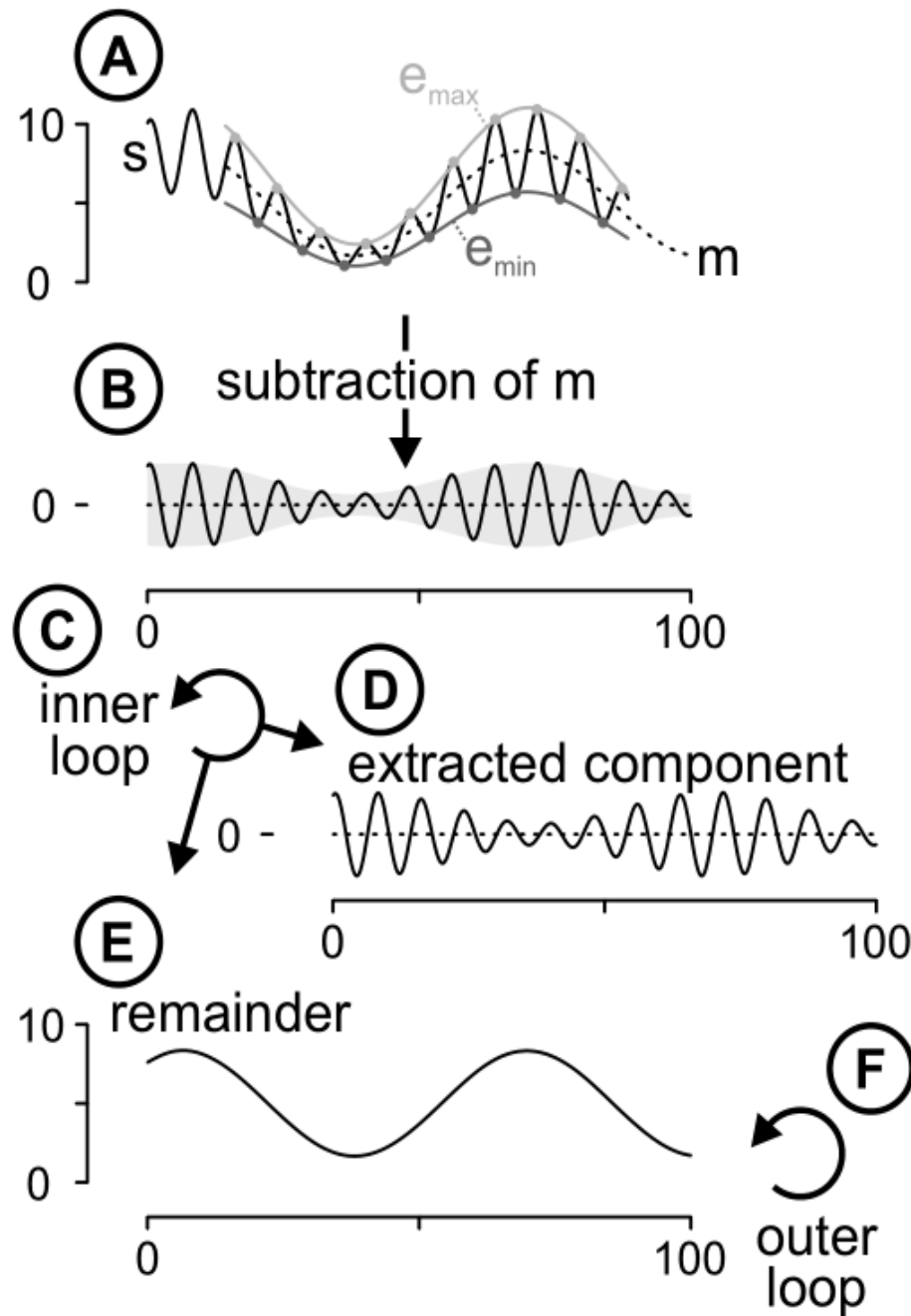
EMD algorithm



EEMD algorithm

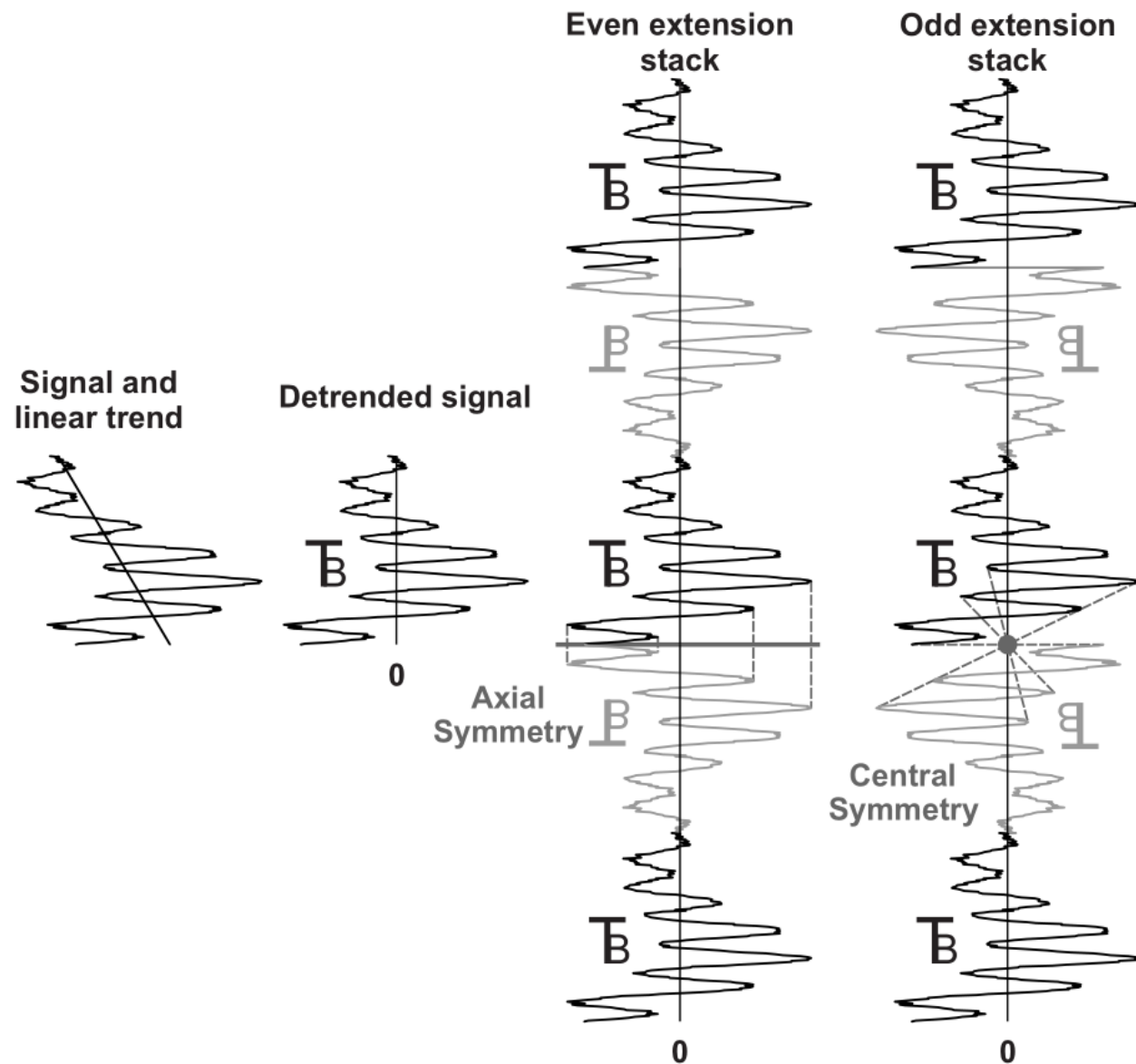
ENSEMBLE Empirical Mode Decomposition

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



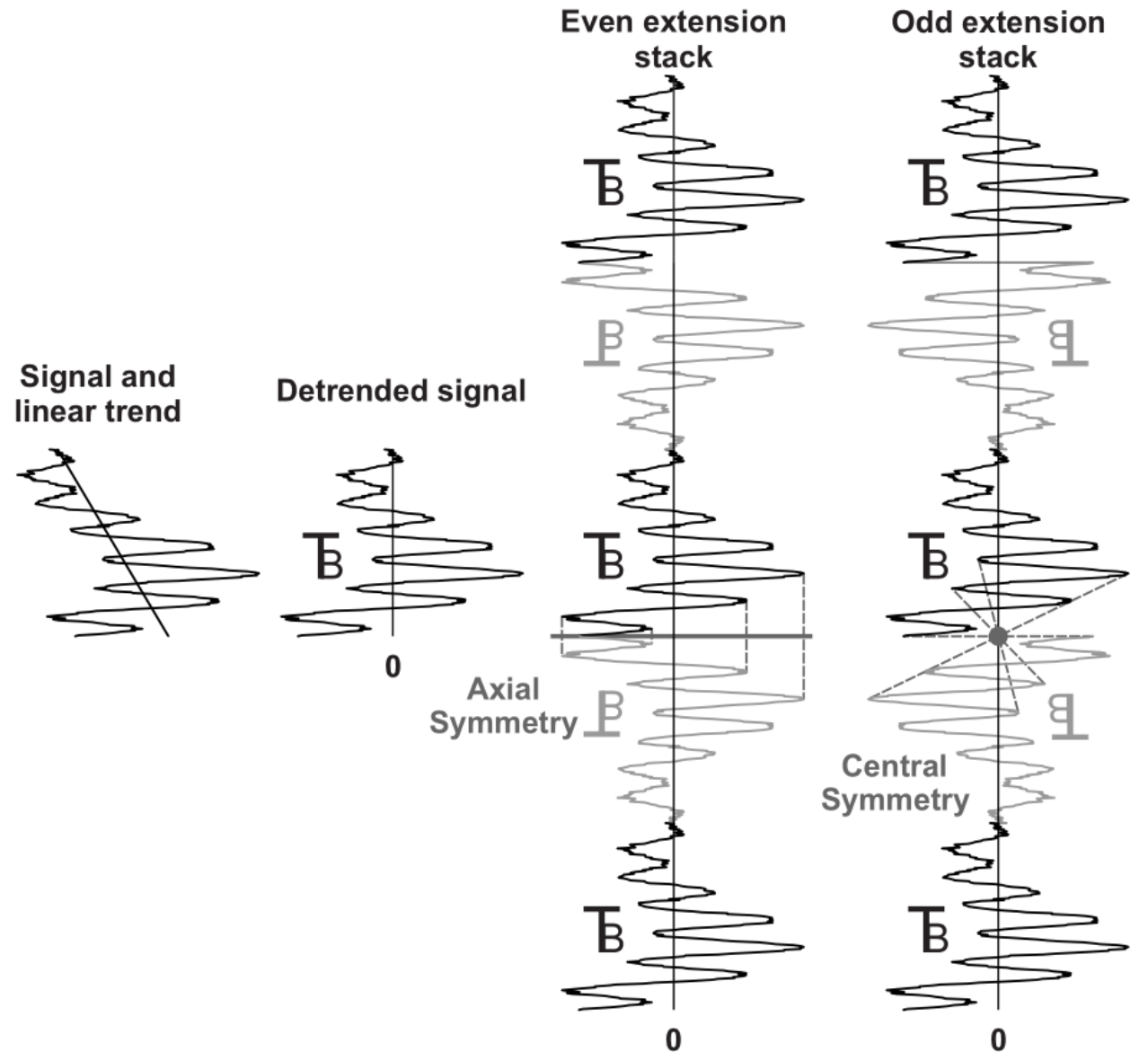
Extricate algorithm (in R)

- ▶ 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**

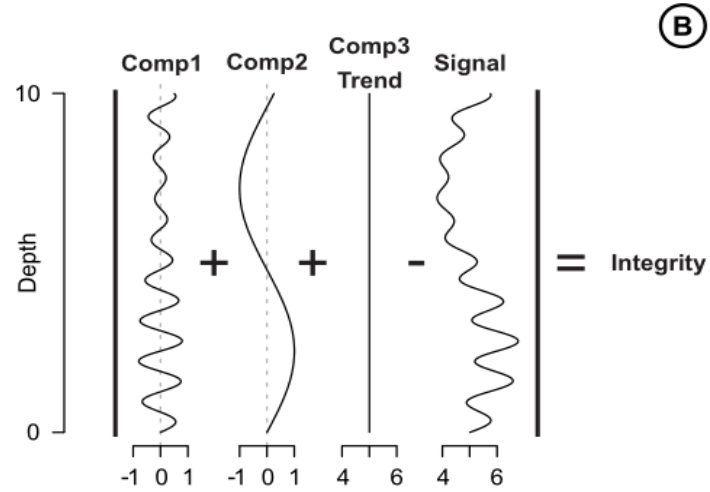


Conclusion

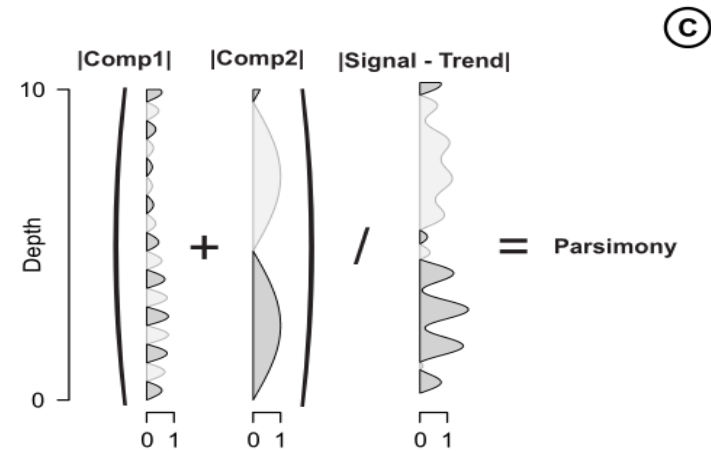
The background features abstract, overlapping geometric shapes in various shades of green, ranging from light lime to dark forest green. These shapes are primarily located on the right side of the slide, creating a modern, layered effect. The rest of the slide is a plain white background.

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 $\Delta 18\text{O}$ Records'. *Paleoceanography* 20 (1). <https://doi.org/10.1029/2004PA001071>.
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- ▶ 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>.