Milankovitch cycles -- Spectral Analysis Procedure

Main references:

Weedon, G.P. (1993) The recognition and stratigraphic implications of orbital-forcing of climate and sedimentary cycles. In: *Sedimentology Review* (V.P. Wright, ed.); Blackwell Publ. (Boston), p.31-50.

National Instruments Corporation (1994) *LabVIEW Analysis VI Reference Manual*. (National Instruments Corporation; Austin, TX): 12 chapters, 3 appendices, various paginations (ca. 500 pages).

Spectral analysis

A. Theory (Power-spectral analysis of a time series)

Power-spectral analysis is performed on values of a parameter obtained at constant intervals of time or space.

Principle of Fourier Transform:

Fourier transform = representation of a signal in the frequency domain.

Discrete Fourier Transform -- A series of discrete points (not a continuous curve) can be represented by the sum of cosine-sine waves.

Transform time-series x_i to fourier-series X_k

The points x_j can be represented by sum of Fourier constants:

$$x_j = (1/N) * \sum (k = 0 \text{ to } N\text{-}1) \text{ of } X_k\, e^{+i\, 2\pi\, j\, k/N}$$

For j = 0 to N-1

Note that $e^{+i\, 2\pi\, k/N} = \cos(2\pi\, j\, k/N) + i * \sin(2\pi\, j\, k/N)$

Or, the Amplitude of Fourier series $X_k = \sum (j = 0 \text{ to } N\text{-}1) \text{ of } x_j\, e^{-i\, 2\pi\, j\, k/N}$

Note that $e^{-i\, 2\pi\, j\, k/N} = \cos(2\pi\, j\, k/N) - i * \sin(2\pi\, j\, k/N)$

For k = 0 to N-1

Fast Fourier Transform (FFT) = rapid procedure for Fourier transforms, but requires 2^n points.

If input data is “time series”, then resulting power spectra is “frequency per unit time”

If input is a “distance series” in meters, then power spectra is “frequency per meter”

Output:

Spectral space (‘0’ order; 1st order; etc.) = amplitude of cycle-order in window

*Output (numerical) = complex series of Xk = Real part + i * Imaginary part*

= amplitude and phase-offset of cycle

<u>Plot of power spectra</u> ***(more details later)***
Horizontal axis = frequency (cycles per entire window)
Which can be converted to cycles per meter, hence wavelength of the particular cycle
Vertical axis = "power" = squared average amplitude of each regular component sine and cosine wave
Cyclicity identified by significant "peaks" in this spectra = significant "power" at that wavelength

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B. Geological data is not a time-series; but a depth-series

The collection of parameter-values is called a "*time series*", even if these are function of distance, rather than time.

"Linear Period" (= cycles per meter)
Wavelength = meters per cycle = [1 / Period]

Conversion to time => need to know sedimentation rate
Elapsed time is NOT (sedimentation rate * thickness). May have hiatuses; etc.

A critical **assumption** when converting "cycles per meter" to "cycles per time" is:
"Distance between successive points in the series represents a constant time interval."
=> sedimentation rate is constant at all scales equal or larger than the sampling distance
Later, we will return to "reality" of geological systems, and whether this assumption needs to be strictly true; when discussing "tuning"

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C. Methods (and software packages)

<u>Methods</u>
Walsh = best for Binary signal (Lms/Clay)
Fourier better for digital (logging) signal
Fast Fourier Transforms = data-array must be power of 2 (e.g., 256, 512) = major limitation on sliding windows
In general, results from cycle analysis (e.g., a cosine-wave) should be visually apparent in the data.
Overlay spectral-peak and de-trended or band-filtered data

<u>Software</u>
Excel = up to 1024 data points for FFT (only). Easy to use for initial exploration of data. Costs about $99 (university price).
Matlab = can handle larger sets for FFT, but interface is less user-friendly. Costs about $150.
LabVIEW = easy to apply filters, windows, etc. Handles enormous data sets. Costs about $1000.
Geophysical tool kits on Unix systems. Very powerful.

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D. General Procedure -- Initial Data Array

Decisions:

(1) What parameter will be recorded for characterizing cyclicity?

Using multiple parameters, perhaps with varying resolutions, is a good method

(2) What should the spacing of data be?

What is the shortest wavelength of cyclicity desired in the analysis?

Can intermediate data points be interpolated?

(3) How many data points are required

Length of available record, restrictions by FFT, ability to smooth the data

Coding data

Digitizing (log, photo, carbonate, lithology), etc.

Considerations during Coding:

(1) Impact of diagenesis on the paleoclimate proxy

Isotopic distortions during cementation, bioturbation mixing, etc.

(2) Treatment of "event beds"

Spectral analysis is not dependent upon an undistorted record, but inclusion of major turbidites and slumped intervals will add background noise

One possibility -- remove turbidite beds to create an artificial "event-free" stratigraphic column

Example: Cyclicity of Lower Cretaceous cyclic carbonates of central Atlantic (Ogg, 1987; Huang et al., 1993)

It is also possible that the changing abundance or character of turbidites, storm beds, or other sedimentation may provide another type of climate proxy.

Example: Spectral analysis of flysch in Ligurian Alps (Foucault et al., 1987)

(3) Simultaneous coding of different parameters (e.g., carbonate content, eolian dust content, isotopic ratios) from the same succession

Opportunity for cross-spectral methods and investigation of interrelationships among different proxies -- relative time lags and relative responses to different cycle periods for processes in the geological record

Example: Pleistocene paleoceanography (Imbrie et al., 1995)

A Few Coding Possilities (modified from Weedon, 1991):

Parameter	Example
Field Observations	
Rock type index	Paleogene pelagic carbonates of Gubbio, Italy (Schwarzacher, 1987)
Facies-depth index	Triassic lacustrine beds of eastern U.S. (Olsen and Kent, 1996)
Bedding thickness	Mid-Cretaceous pelagic sediments in Italy (De Boer, 1982)
Color (color densitometry)	Aptian-Albian pelagic sediments of Italy (Herbert and Fischer, 1986)
Grain size	Oligocene shelf clastics of Belgium (Van Echelpoel and Weedon, 1990)
Paleontological Data	
Fossil assemblage index	Turonian Chalk of England (Cottle, 1989)
Fossil abundance index	Turonian Chalk of England (Cottle, 1989)
Logging or Geophysical Measurements	
Gamma ray log	Upper Cretaceous chalk of central U.S. (Laferriere and Hattin, 1989)
Resistivity log	
Magnetic susceptibility log	
Spectal-reflectance log	Eocene-Paleocene chalks of eastern U.S. margin (ODP Leg 171, 1996)
Geochemical Measurements	
Carbonate percent	Aptian-Albian pelagic sediments of Italy (Herbert and Fischer, 1986)
Organic-carbon percent	Kimmeridge Clay (Weedon and Jenkyns, 1990)
Oxygen & Carbon isotopes	Upper Cretaceous chalk (Ditchfield and Marshall, 1989)
Silica/Aluminum ratio	Aptian-Albian black shales of Italy (Herbert et al., 1986)
Salt percent	Ordovician evaporites of Australia (Williams, 1991)

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Density and Resolution of Data

Requirements on data density

Higher density of data => can resolve higher frequencies of cycles

Require at least 2 points within cycle wavelengths to resolve that cycle.

Nyquist frequency = 2 points per cycle

Sampling below Nyquist frequency causes artifacts due to inadequate sampling of cycle ("Aliasing")

Fine-scale data (e.g., FMS imagery, core-scanners, or some natural gamma) => shortest cycle of interest may be "over-sampled"

=> One has the flexibility to reduce noise by a sliding-average (e.g., 3-point sliding mean)

Resolution of data

Window and data-collection-rate of logging tools => limits resolution of short-term cycles

If the window is longer than the wavelength of the cycle, then such cycles will be essentially "filtered" from the series.

However, this smoothing of the signal will not produce aliasing.

Over-averaging = loss of ability to detect short-period cycles; but Under-sampling will cause artifacts!

Aliasing

If data spacing is too far apart, then small-scale variations are incompletely recorded.

Creates artifacts of spurious long-wavelength oscillations (harmonic of data spacing with the shorter-period cyclicity).

Beware of any "cycle" that has a wavelength that is a multiple of the sampling-interval.

Solutions:

Use pilot study with very closely-spaced sampling to look for short wavelengths, then adjust data stream accordingly

Use a smoothing to remove the shorter frequencies.

Bioturbation mixing will often naturally smooth out high-frequency cycles => rarely necessary, except in laminated sediments, to have data spaced closer than 1cm.

Interpolation of data

Software (FFT) is generally designed for evenly-spaced data

=> may need to interpolate (e.g., Newark lithology data)

Interpolation interval should be larger or equal to average sample interval to avoid bias.

Requirement for 2^n values => may need to "pad with zeroes" to add a leader or trailer.

Do zero-padding after de-meaning, filtereing, and tapering the data -- it should be the final step before spectral analysis.

Adding zero-trailers will change the spectral-order (within the broadened window) and amplitude of peaks, but not their relative wavelengths.

Requirements on window for spectral analysis

(1) Must encompass at least 4 or 5 cycles of longest period of interest

(2) Must avoid spanning major changes in facies (sedimentation rates) that are not caused by Milankovitch processes

(3) Longest practical data file would incorporate 4 repetitions of 400 k.y.

Longer periods (1.2 m.y.) are reported (e.g.; Newark), but requires exceptional stability of depositional environment (need to have at least a 5 m.y. record with stable sedimentation rate). Of course, these longer periods may be the cause of sequence boundaries which are causing high-lowstand contrasts in facies (to be discussed later).

(4) Sliding windows => can see stability and drift of significant peaks through section = measure of changing sedimentation rates

(5) Narrower windows => less distortion due to sedimentation rate changes, but also loss of long-period cycles

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Exercises on Sampling and Resolution

(1) Suppose actual sedimentation rate is 10m per m.y. (typical open-oceanic sediments -- e.g. Cretaceous of DSDP 534).

(a) How many points are needed per meter to identify 100 k.y. Eccentricity, 41 k.y.Obliquity, and 20 k.y. Precession?

(b) How long a record is required for a statistically significant identification of the 400 k.y. Eccentricity cycle?

(c) To obtain the entire suite of statistically significant 20 k.y. through 400 k.y. cycles, what is the minimum number of required data points, and spaced over what interval?

Solutions:

(1) (a) 1 m.y. = 10m => 100 k.y. = 1m, and 20 k.y. = 20cm

Desire at least 2 points per cycle => 100 k.y. requires 50cm spacing; 20 k.y. needs 10cm spacing; 40 k.y. needs 20cm spacing

(b) 400 k.y. = 4m. Need about 5 cycles in interval => 20m would be adequate

(c) 10cm intervals for 20m => 200 points are the minimum

(2) In the previous example, what cycles can be identified with the following logs:

(a) Any typical log data array (sampling = every 15cm)

(b) Natural-Gamma logs (resolution = 25cm)

(b) Spherically-focused Resistivity (resolution = 50cm)

Solutions:

(2) (a) Normal log data sampling is inadequate for Precession (20 k.y.; which needs 10cm sampling)

(b) Gamma logs would be entirely blur Precession, and would be barely adequate for 40 k.y. Obliquity (which needs 20cm spacing)

(c) Resistivity will only be useful for Eccentricity-type cycles in these sediments

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E. General Procedure -- Filtered Data Array

Philosophy:

(1) Output of Fourier analysis is the distribution of total "power" over all periods.
Therefore, if remove long-period trends (longer than 2 wavelengths within window) ***and*** short-period "noise" (variability below resolution of data to detect cycles), then more power will be available to improve signal-to-noise of other peaks.

(2) Abrupt terminations of the data series will also be modeled by Fourier method.
Therefore, wish to reduce these "additional" frequencies.

De-meaning

Removing large "zero-order" term ("DC offset") from the spectra
=> center the data series around "0"
= subtracting mean within the window from each data point

This procedure causes no loss of any primary cycle signals of any wavelength.

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Filtering ("White" and "Red" noise)

The final spectra is the distribution of power at all component frequencies that are required to model the input data.

If some sources of small-scale variation and of very long-term non-cyclic trends within the window can be removed, then more "power" will be apparent at possible component cycles.

Filtering, if carefully applied, can aid in resolution of peaks, by removing the "drain" of power from the intermediate wavelengths

(1) High-frequency "white noise"

"*White*", because it is all wavelengths

Desire to reduce or remove the "white noise" that drains power from low-frequency peaks, but implies a reduction in ability to identify high-frequency cycles.

Methods to reduce "white noise:

Applying moving "3-point mean" to the data array

Note that this requires at least one data point above and below the 3-pt-mean-sliding-window!
A 512-point window will require a "0" and a "513" data-point to compute the mean at the ends.

(2) Removing long-term drifts within window ("red noise")

"*Red*", because it is the long-wavelengths in the spectra

Typically, the very long-term trends will dominate the apparent "power" of the spectra -- largest peaks are at the lower frequencies.

These "long-term" trends are those that only have an apparent single or double "cycle" variation within the window, therefore are not statistically significant, even if they are caused by Milankovitch.

Non-cyclic long-term trends, oscillations, and their harmonics will remove power from the higher-frequency cycles => spectra is more difficult to interpret

=> Must decide what long-period frequencies are important (usually from visual observation of signal for apparent non-cyclic long-term "drift" in facies)

<u>Methods to reduce "red noise":</u>

Remove wavelengths of order "1" and "2" (only 1 or 2 "cycles" within the window)

Subtracting multi-point sliding mean centered about each point

(e.g., 512-point series can be de-trended by subtracting a 256-point sliding mean. 257-point average, with 128 above, 1 data, and 128 below)

Note that this requires that the data series extend beyond the window by at least this amount!

A 512-point window will require an additional 128 points above, and below, the window.

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Tapers

Finite sampling record => Truncated window

=> Abrupt start and stop of data

=> Spectra will contain artifacts from Fourier-transform of these "ends"

"Spectral energy leakage" from the cycle peaks; Introduction of harmonics of the window-length

Desire to minimize the transition edges

Tapering "ends of data" reduces the contrast, but also slightly diminishes the cycle signal.

Most Common Methods:

(1) Cosine Window (Hanning Window)

Entire series is tapered to a full-cosine rise-fall

For j = 0 to (N-1)

$$\text{New-}X_j = \text{Old-}X_j * 0.5 * [1 - \cos(w)]$$

where, $w = j * 2\pi / N$

and N = total number of elements

(2) Split-Cosine Window

Cosine rise is applied to front (10%) and Cosine rise to the end (10%)

For j = 0 to (N-1)

$$\text{New-}X_j = \text{Old-}X_j * 0.5 * [1 - \cos(w)]$$ for first 10%, and last 10% of series

and $\text{New-}X_j = \text{Old-}X_j$ for the middle 80% of the series

where, for first 10% (j = 0 to N/10) $w = j * 2\pi / T$

and for last 10% (j = [N - N/10] to [N-1]

$w = [(N-1)-j] * 2\pi / T$

and T = 20% of Total number (N), because 10% rise + 10% fall is one wavelength

(3) Triangular

(4) Multiple-taper (Thomson) = best method, and provides statistics on confidence by combining first five-orders of tapers; but is not as easy in Excel

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F. General Procedure -- Interpreting Output Array

Output

Spectral space ('0' order; 1st order; etc.) = amplitude of cycle-order (frequency) in window

*Output (numerical) = complex series of Xk = Real part + i * Imaginary part*

= amplitude and phase-offset of cycle

If input = 512 points, then output = amplitude of "0" to "511"-order sine and cosine cycles.

Symmetric about mid-point ("255") due to *cosine vs. sine symmetry* => ignore 2nd half.

$$X_i = X_{(N-i)}$$

Complex numbers array from "0"-order to "total-point" order.

Array:

X(0) = DC component

= "0" order = first data point = offset of the array from the axis and linear-component of long-term drift

X(1) = 1st harmonic = amplitude of cycle spanning full window

= "1" order = second data point = amplitude of 1 cycle-wavelength within the window

X(2) = 2nd harmonic = amplitude of double-cycle spanning full window

X (N/2) = Nyquist harmonic

X (N-2) = 2nd harmonic (again)

X (N-1) = 1st harmonic (again)

There is no X(N) in array

Note that 0 to (N-1) = N points

Amplitude = absolute value of the complex spectral-amplitude (drop the phase-shift component)

=> use "IMABS" function in Excel

Power = Square of Amplitude

Typically, Blackman-Tukey graphic method is to display "relative power" (= relative variance density)

= dividing all "power values" by sum of these values

Enables a partial estimate of the relative importance of a cycle to the complete series.

Hanning filter *= partial removal of "ringing" of 1st-order term (?)*

*= 0.5 * spectral-point + 0.25 * both adjacent points (after taking amplitudes)*

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Plot of Power Spectra

Plot:

Spectral amplitudes, or power, or relative power (all will yield the same peaks, but peaks are enhanced more with "power"

vs. cycles/window (remember that 1st output-value is the "zero-order"!)

<u>Plot of power spectra</u>

Horizontal axis = frequency (cycles per entire window)

= integer values (a limitation on resolution of cycle wavelengths, especially for longer ones)

Which can be converted to cycles per meter, hence wavelength of cycle

Vertical axis = "power" = squared average amplitude of each regular component sine and cosine wave

IMABS = absolute value of complex number -- due to cosine-sine = e^{ix}

Typically, Blackman-Tukey graphic method is to display "relative power" (= relative variance density) = dividing all "power values" by sum of these values

Enables a partial estimate of the relative importance of a cycle to the complete series.

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Peaks

Cyclicity identified by significant "peaks" in this spectra = significant "power" at that wavelength

General analysis procedure

Identify peaks

Convert center-of-peak to equivalent wavelengths

Compare ratios to Milankovitch period-ratios

Assign Milankovitch peaks, and harmonics

Distinguishing Real Peaks from Background

Fourier analysis of a time series is based on a finite number of Points (not curves), therefore the output spectra is an approximation to the spectrum that would be derived from an infinitely long series.

Specta will contain "unwanted" spurious peaks and troughs that result from having a limited number of data points, and the mathematical modelling of all features in the data array (including end truncations)

(1) "Use confidence limits applied to a log power vs. frequency plot." => derive 90% and 98% confidence levels on peaks above noise.

(2) Split time series into two halves, or a sliding window that is less than half the thickness of the main window. Check that the same peaks are present in both subseries or maintain a stable relative relationship to each other.

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G. Testing for Milankovitch cycles

Ratio test

IF Ratios of wavelengths (or "depth-periods") = Ratios of certain Milankovitch time-periods
Then, sediment cyclicity is probably a Milankovitch orbital signal of those periods
Suite of 413-123-95-41-23-19 k.y. periods
=> have independent measure of time represented by sediment package

Problems:

(1) Long-period cycles have a lower integer-number within the window => precision of these peaks' wavelengths are not as accurate => misleading ratios
(2) The abundance of Milankovitch periods and their possible drift with time (but disputed) imply that the ratio test may not yield a unique answer
(3) Wavelength ratios can be altered by presence of hiatuses or slumps (affect positions and broadening of longer-period cycle peaks more than shorter-period cycle peaks)

Bundling test

Eccentricity modulation of precession => IF precession is dominant signal within an interval, then should have an envelope of amplitude of these cycles.
100 k.y. => repeating pattern of 5 precession cycles of 20 k.y.
Easy "field" test

Problems:

(1) The 100 k.y. modulation is actually a 95 k.y. and 123 k.y., plus the 400 k.y. long-period eccentricity, plus the dual 19 k.y. and 23 k.y. precession cycles => bundling will not be consistent. <u>Lack</u> of regular bundling is <u>**not**</u> an argument <u>against</u> this type of cyclicity.
(2) Random variations of bed thicknesses or other parameters will inevitably produce some "bundling" clusters. Therefore, the <u>presence</u> of sporadic bundling is <u>**not**</u> an argument <u>for</u> this type of cyclicity.
(3) Precession cycle may have been shorter in Paleozoic or early Mesozoic => would expect more than 5 precession events per eccentricity-modulated bundle.

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H. Isolating and examining behavior of regular cyclicity in the signal

Band-pass Filtering

Once a regular cyclicity has been resolved by spectral analysis, the original signal can be processed to enhance this desired wavelength (bandwidth) = "bandpass filter"

Low-pass filter = removing all higher-frequency components

One method: Repeated application of a weighted three-point moving average

High-pass filter = removing all lower-frequency components

One method: Subtracting a sliding multi-point mean from the data

Band-pass filtering allows the wavelengths of interest to be separated from the original array.

Allows comparison of spectral analysis results to the original signal.

Allows examination of changing amplitude of these cycles within the succession

(The amplitude of cyclicity is NOT easy to determine from the output of spectral analysis)

Cross Spectra (Coherency, and Phase)

Coherency spectra:

Test whether amplitude variations in two data sets are linearly correlated

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I. Phase shifts among factors (see Ice Age example)

Multiple types of data within same window (e.g., Carbonate-percent; Oxygen-isotopes (both planktonic and benthic), Carbon-isotopes (both planktonic and benthic); Temperature-sensitive ratios of foraminifer; Eolian dust; etc.)

Phase spectra:

Phase spectra indicates for a particular frequency in two time series, if these cycles vary synchronously or are offset (phase-shifted)

Example:

Do isotopic ratios change simultaneously with carbonate abundances within a succession?

Create time series for isotopes, and for carbonate abundance, for this same succession (interval of time).

Compare phase relationships between the spectral peaks within each time series for the same window.

Spectral peaks for each parameter's time series may have:

(1) differing relative amplitudes (strong 100 k.y. and 20 k.y. vs. strong 40 k.y.)

(2) phase offset of peaks (from complex factor in spectral analysis result) among different quantities.

Fix one factor as "reference" and examine relative timing (in "partial cycle" as a "clock" diagram) to see how some factors may have lagged response to changes in others.

Ice Ages -- Milankovitch-predicted spectra = main control; but some quantities "lead" and others "lag".

GIVE Details (Imbrie et al. model)

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Difficulties and Possible Pitfalls in Cycle Analysis

(presented after the lab exercises)

A. Effects of Geological Distortions on Spectra

Most geological processes disrupt a regular time series in the environmental signal, rather than create regularity.

If a regular cyclicity can be detected using a thickness scale

Bioturbation

Tends to smooth trends => a natural "high-frequency filter of white noise".

Diagenetic and Compaction Enhancement

Cyclicity is often enhanced in the geological record

Clay-rich portions of cycles tend to become enhanced by preferential compaction

Carbonate-clay cyclicity will become enhanced by preferential diagenetic redistribution of carbonate from clay-rich zones toward clay-poor zones

=> Sine-wave of original environmental signal becomes distorted into cuspate or square-wave signal.

NOTE: The Earth's climate response to Milankovitch cycles may also exhibit a non-linear response with a rapid threshhold transition between states => original climate signal may not be a sine-wave, but a step-function. Such a threshhold response is observed in the onset and termination of glacial epochs.

Square-wave type signals generates "harmonic peaks" on the power spectra = multiples of the frequency of the dominant peak => subpeaks at shorter harmonic wavelengths

In spectra -- peak at 5th order spectal peak (5 cycles within window) will have secondary "ringing" peaks at 10, 15, 20, 25 order spectra.

=> A pronounced 100 k.y. signal will yield secondary peaks with apparent periods of 50 k.y. (100/2), 33 k.y. (100/3), 25 k.y. (100/4), 20 k.y. (100/5), etc.

Recognition: Check ratio of frequency of secondary peaks to dominant longer-wavelength peaks.

Fluctuations in Sedimentation Rates about the Mean (intermediate-term variations that are non-periodic)

=> A periodic oscillations-in-time will have variable oscillation-in-thickness

=> broadening of peak (and reduction of height)

Cyclic Long-term Productivity or Clastic Influx **(intermediate-term variations that are periodic)**

=> Cyclic changes in sedimentation rate, and possibly in compaction

Therefore, geological thicknesses within the cycles are not a linear time series, but a non-linear relationship to time

Consider an Eccentricity (100 k.y.) signal on Precession (20 k.y.)

=> Precession "beds" will be systemmatically wider during maximum Eccentricity modulation

=> Sine-wave form with time becomes distorted with stratigraphic thickness = stretched in modulation peaks, compacted in modulation troughs

Result on spectra"

(1) Separation of the fundamental Precession into a two-pronged peak

The higher frequency peak = compacted precession cyclicity during Eccentricity troughs; the other is stretched cyclicity during the Eccentricity peaks

Essentially, these two peaks are wavelengths that interfer with constructive and destructive results

(2) Creation of "tone peaks" = peaks at the modulation frequency = Eccentricity

Trends in Sedimentation Rate

Results in continual lengthening or shortening of thickness of cycles through the succession

=> Spectral peaks are blurred = more difficult to recognize low-power peaks

=> Adjacent peaks (e.g., 95 k.y. and 123 k.y.; or 19 k.y. and 23 k.y.) can merge with each other into a broad plateau.

Can distort the signal within the succession so that no well-defined peaks are generated.

Sliding Window may help resolve cyclicity, and allow recognition of sedimentation rate changes

Analyze spectra of overlapping windows

Choice of window size -- ideally try to maintain ability to recognize 100 k.y. peaks => window should incorporate about 500 k.y. of sedimentation

Result: "Evolutionary Spectra" (Priestley, 1981) -- examine for consistency in relative positions of well-defined peaks

Peaks will shift frequency up-section in response to changing mean sedimentation rate => can invert to deduce these sedimentation rates.

Sudden Discontinuity in Sedimentation Rate ***(see Molinie and Ogg, 1991)***

Spectra of entire succession - double suite of peaks, which may overlap and make recognition difficult
Suppose sedimentation rate in top half is Twice the rate in lower half
Top half will have twice the number of cycles relative to the lower half => peaks will be higher

Computation of sedimentation rates:
Sliding Window -- can resolve where one set is replaced by the other set
Use windows above and below the replacement zone and the two sets of positions of the peaks to compute the two different sedimentation rates

Computation of level of discontinuity in sedimentation rate:
Use a series of close-spaced overlapping sliding windows progressively through the zone where the peak shifts occur
When both peaks from the same underlying cyclicity are equal in height (power), then in this window, there are the same number of cycles above and below the discontinuity.
Apply the computed sedimentation rates from the first step, and solve for the relative ratio of sediment deposited with each rate within the window
This ratio, plus the thickness of the window, will indicate the placement of the discontinuity

Hiatus or Slump

(1) If sedimentation rates above, and below, the hiatus are the same within the window, then the frequency of cyclicity will be the same, but with a loss of cycles.
If an integer number of cycles are absent
=> Spectral analysis will yield the same result for this cycle wavelength as for a continual succession
If an additional portion of a cycle is absent
=> generation of additional noise, and broadening of the spectral peak of that cycle

(2) Multiple hiatuses or slumps within the window
=> additional noise in spectral peaks of cycles

In general, there will be different fractional truncations of different cycle wavelengths => hiatuses will alter the ratios of spectral peaks of pairs of cycles.

Important note:
Hiatuses or slumps do not usually alter the ability to detect cyclicity.
Well-defined sets of spectral peaks at Milankovitch frequencies does not imply that every successive cycle is present within the interval, or that sedimentation is continuous.
=> Application of spectral analysis with good Milankovitch signatls to determine time scales will always give a duration that is equal or <u>less</u> than the actual elapsed time within the succession.
However, the result will indicate how much time is <u>present</u> in the preserved sediments.

Problem of undetected gaps:
"There is a tendency of some workers to assume that no cycles are missing in their sections."
(Weedon, 1991)
Deep-sea sediments:
Databases imply that a section spanning one-million years will <u>on average</u> be 86% complete at the 20,000-year scale => an average of 14 out of 100 precession cycles could be missing.
Continental sediments: Can be even more extreme. "Gaps tied together by thin accumulations of sediment."

Suspected Example -- Duration of Cenomanian stage
De Boer (1982) -- Italian sections. Cenomanian = 7.0 m.y.
Gale (1989) -- composite of couplets in most complete British Cenomanian in Chalk, and observation that these were often in bundles of 5
=> precession modulated by eccentricity
=> Cenomanian = 4.4 m.y.
Difference may be presence of numerous discontinuities within the British Chalk - basin-wide sequence boundaries.

Summary
Significant spectral peaks with stratigraphic thickness indicates a regular cyclicity in time.
Absence of spectral peaks implies <u>either</u>:
(1) Absence of regular cyclicity expressed in the original depositional environment
or (2) The original regularity has been distorted in the conversion of time to depth

Cycles provide a minimum estimate of interval duration.
Feasible when the period of regular cyclicity can be estimated accurately, and when many sections can be correlated to check for gaps.

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B. Artifacts of the Spectral Analysis Method

Resolution of peaks
(1) Peaks are represented by Integer repetitions within the window
=> difficutl to resolve a Non-integer period in window:
Suppose have 40m window with 9m wavelength peak => will fall between wavenumbers of 5 (8m) and 4 (10m) => must guess that peak is mid-way between.
Suppose have 11m wavelength => see a peak at 4 cycles/window (10m) with minor shoulder at 3 (13m) => difficult to derive the exact 11m answer.
Fluctuating sedimentation rate = "blurred" (wider" peaks) about mean
Discontinuity in sedimentation rate = dual-sets of peaks; offset from each other

Artifacts of spectral analysis

Harmonics of cycles (400 k.y./2; 400 k.y./3; etc.)

Example: 10 k.y. cycles in Newark analysis = real feature (proximity to equator) or artifact (21 k.y./2; 19 k.y./2)?

Window aliasing => ringing (show example from the Physics spectral-analysis time-series book) = harmonic of window length (40m/2; 40m/3)

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C. Non-Milankovitch Cycles

Milankovitch vs. other cycles

Non-cyclic "cycles"