



The Lomb-Scargle Algorithm

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What is it?

- Lomb-Scargle methods are a way to analyse signals with inconsistent time series
- Generates data on underlying periodicity

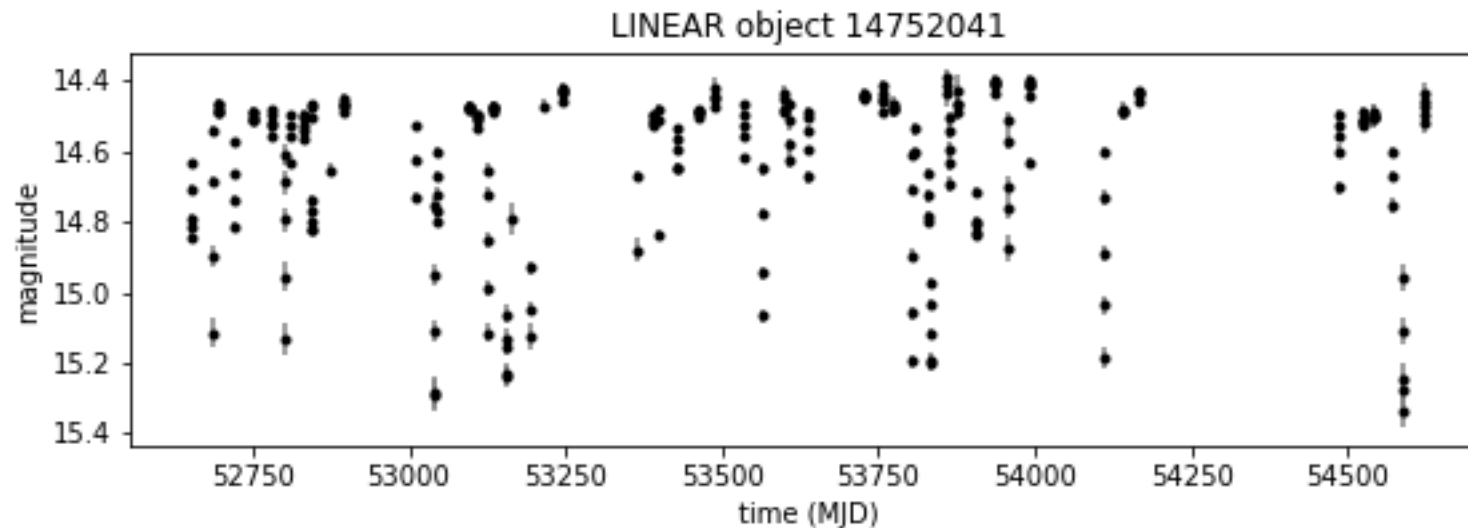


FIG 1. Example data showing light intensity of a star (LINEAR catalogue number 14752041) over time.

Where is it used?

- Many applications where it is not possible to constantly record, or there are gaps in records of past events.
- Sees heavy use in astronomy – weather, day/night cycle, seasonality all can prevent consistent data capture
- Important in climate science – used to deal with gaps in sediment and ice cores

What is a Periodogram?

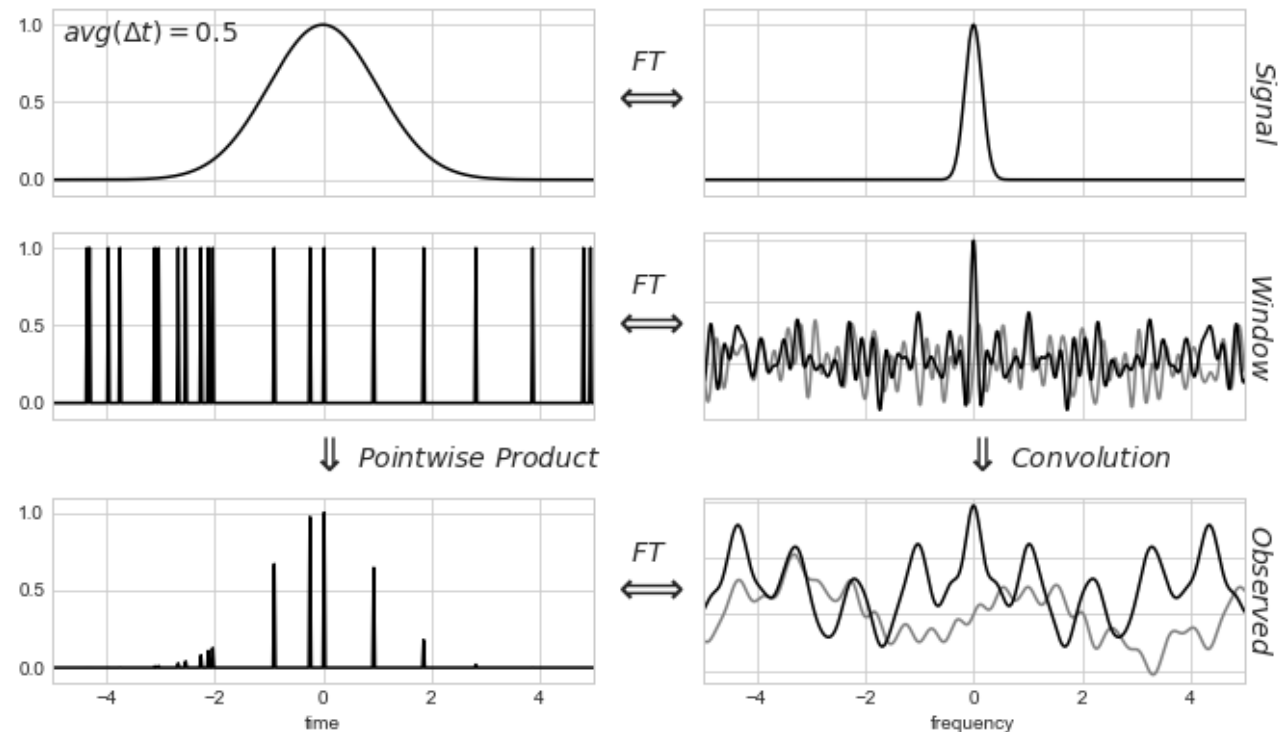
- An estimate of the power spectral density, characterizing the signal in terms of the power of each frequency
- The classical periodogram is the square of the Fourier transform, and can be computed with the DFT

$$S(\omega) = \frac{1}{N} \left\| \sum_{j=1}^N x(t_j) e^{-i\omega t_j} \right\|^2$$
$$= \frac{1}{N} \left(\left(\sum_{j=1}^N x_j \cos(\omega t_j) \right)^2 + \left(\sum_{j=1}^N x_j \sin(\omega t_j) \right)^2 \right)$$



Why not FFT?

- For the FFT, an uneven delta-comb sampling window is asymmetric, and has a noisy Fourier inverse. This gives a noisy result.
- Spectral leakage from high frequencies to low frequencies is also a common problem



Mathematics

- Relies on Fourier series. Instead of Fourier transforming the data straight away, it determines the frequencies of interest, then fits coefficients to the frequencies using a least-squares method.

$$\phi \approx \mathbf{A}x$$

$$\mathbf{A} = \begin{bmatrix} \sin(\omega_0 t_0 + \phi_0) & \sin(\omega_1 t_0 + \phi_1) & \dots & \sin(\omega_n t_0 + \phi_n) \\ \sin(\omega_0 t_1 + \phi_0) & \sin(\omega_1 t_1 + \phi_1) & \dots & \sin(\omega_n t_1 + \phi_n) \\ \vdots & \vdots & \ddots & \vdots \\ \sin(\omega_0 t_n + \phi_0) & \sin(\omega_1 t_n + \phi_1) & \dots & \sin(\omega_n t_n + \phi_n) \end{bmatrix} \quad x = \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \end{bmatrix}$$



Choosing Frequencies

- Different frequencies may be selected for the A matrix. A good selection of frequencies can improve results.
- The minimum frequency is often set as the inverse of the test duration
- The maximum frequency is often based on the Nyquist frequency.
 - The Nyquist frequency doesn't apply for non-uniform data. We can use an approximation for a benchmark. (We can actually find patterns below Nyquist)
 - The frequency is then oversampled for safety
 - Non-uniform Nyquist model:

$$t_n = t_0 + k * p, k \in \mathbb{N}$$

$$f_{Ny} = \frac{1}{2p}$$

Phase

- Each frequency should be fit to both amplitude and phase. We will fit the phase first, then fit the amplitudes.
- The phase should shift the proposal wave to have a maximum at the maximum of the given data
- The phase τ is calculated for each frequency f by:

$$\tau = \frac{1}{4\pi f} \tan^{-1} \left(\frac{\sum_n \sin(4\pi f t_n)}{\sum_n \cos(4\pi f t_n)} \right)$$

Power

- The least-squares method result is the following equation:

$$P(f) = \frac{1}{2} \left(\frac{\left(\sum_n g_n \cos(2\pi f[t_n - \tau]) \right)^2}{\sum_n \cos^2(2\pi f[t_n - \tau])} + \frac{\left(\sum_n g_n \sin(2\pi f[t_n - \tau]) \right)^2}{\sum_n \sin^2(2\pi f[t_n - \tau])} \right)$$

Error

- The previous equations rely on some approximations, namely:

$$\sum_{n=1}^N \cos^2(2\pi f t_n) = \sum_{n=1}^N \sin^2(2\pi f t_n) = \frac{N}{2}$$

- This error is χ^2 distributed, meaning we can calculate the likelihood that a peak is due to periodic behavior.

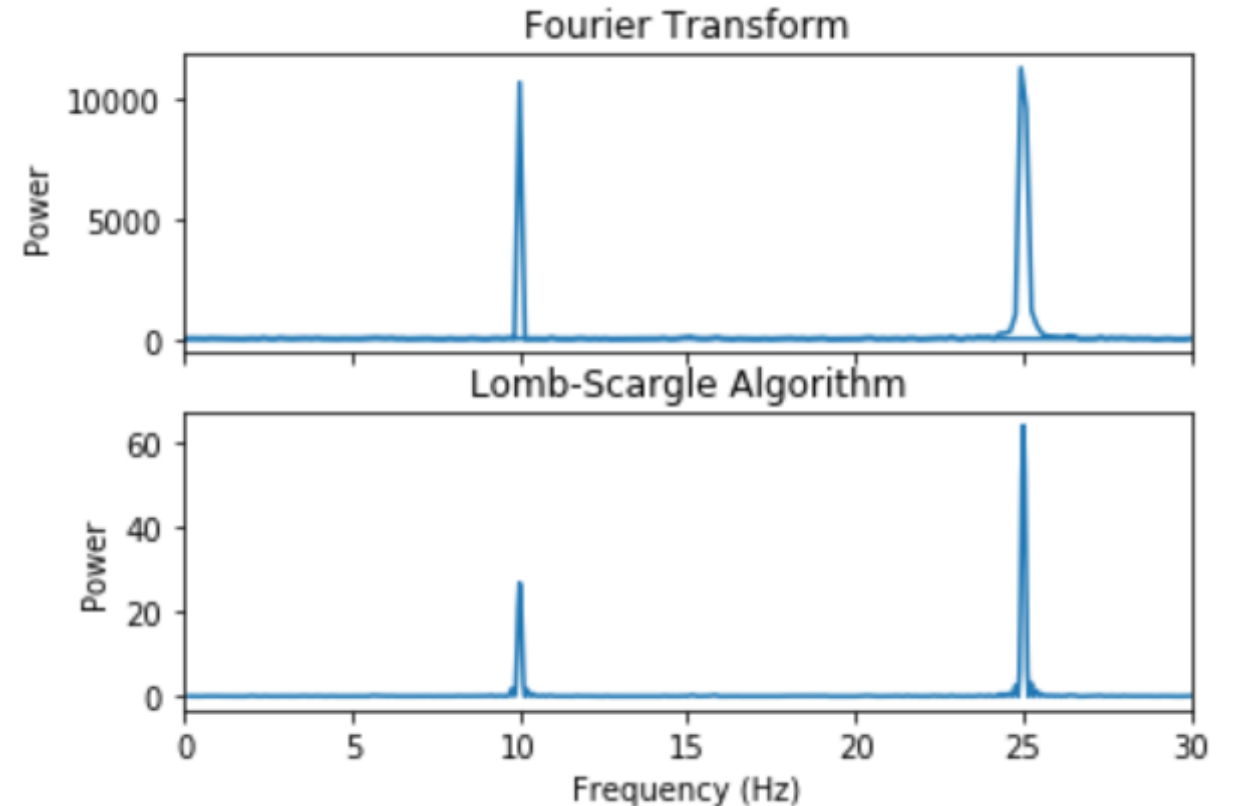
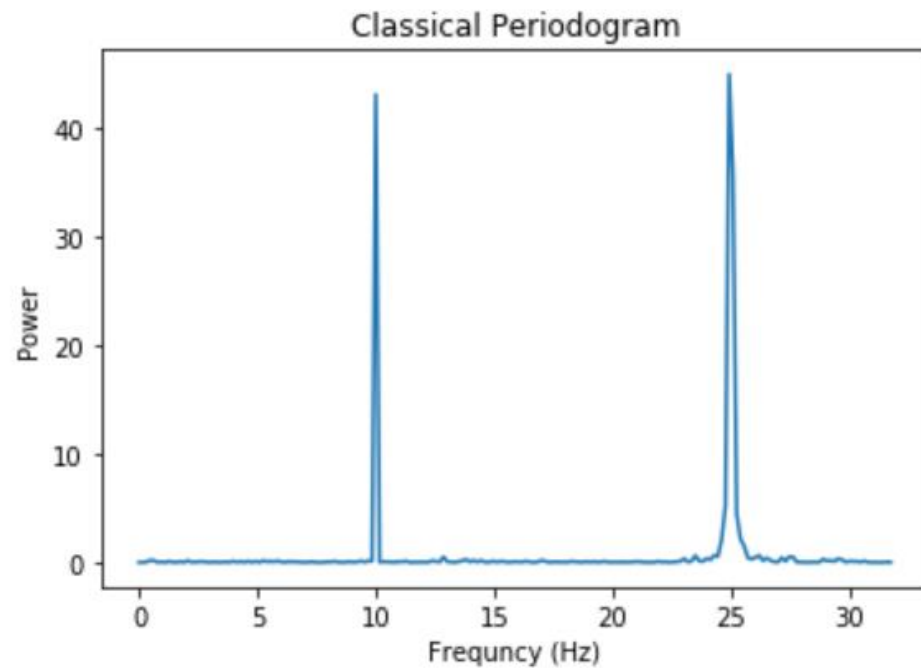
Lomb-Scargle vs. FFT

- The Lomb-Scargle algorithm operating at order $O(n)$ whereas the DFT and FFT operate at order $O(n^2)$ and $O(n\log_2(n))$, respectively.
- When you can use both Lomb-Scargle and FFT, FFT is actually faster. This is because Lomb-Scargle relies on oversampling.

Example: Mathematical

Simple example signal

$$\frac{1}{2}\sin(2\pi 10t) + \frac{4}{5}\sin(2\pi 25t)$$

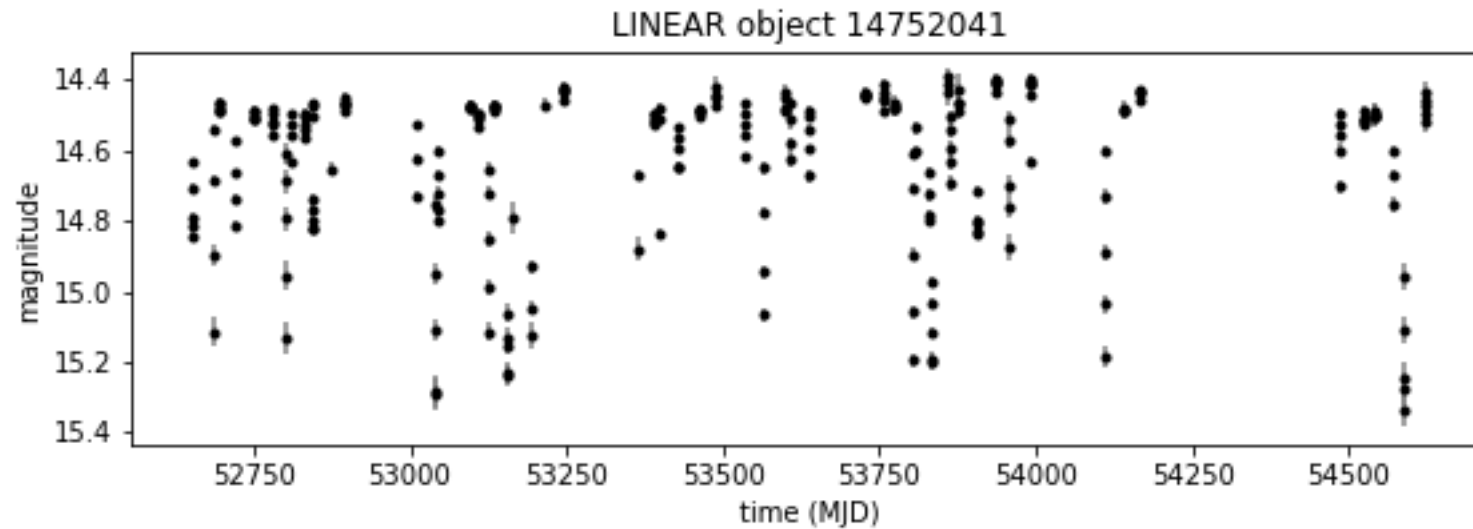


Astropy

- Astropy has developed a simple class for handling Lomb-Scargle periodograms

Pros	Cons
Object-oriented	Automatically sets the A matrix
Simple commands	Manual selection of A values far less simple
Includes 6 different algorithm implementations	Can't handle error in time measurements
Can handle error in signal amplitude	
Built-in tests for units, significance	

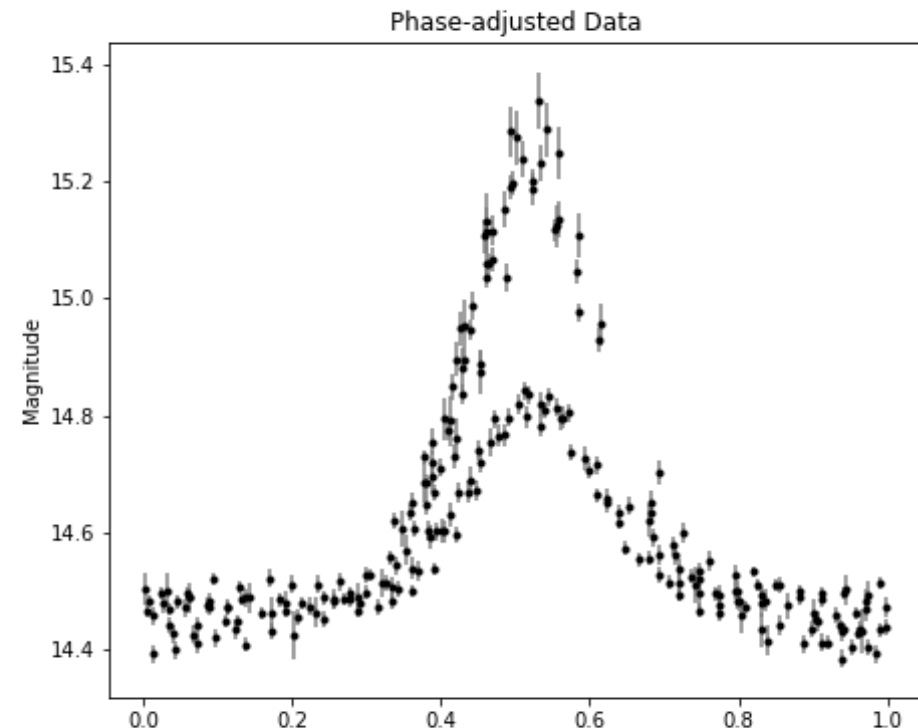
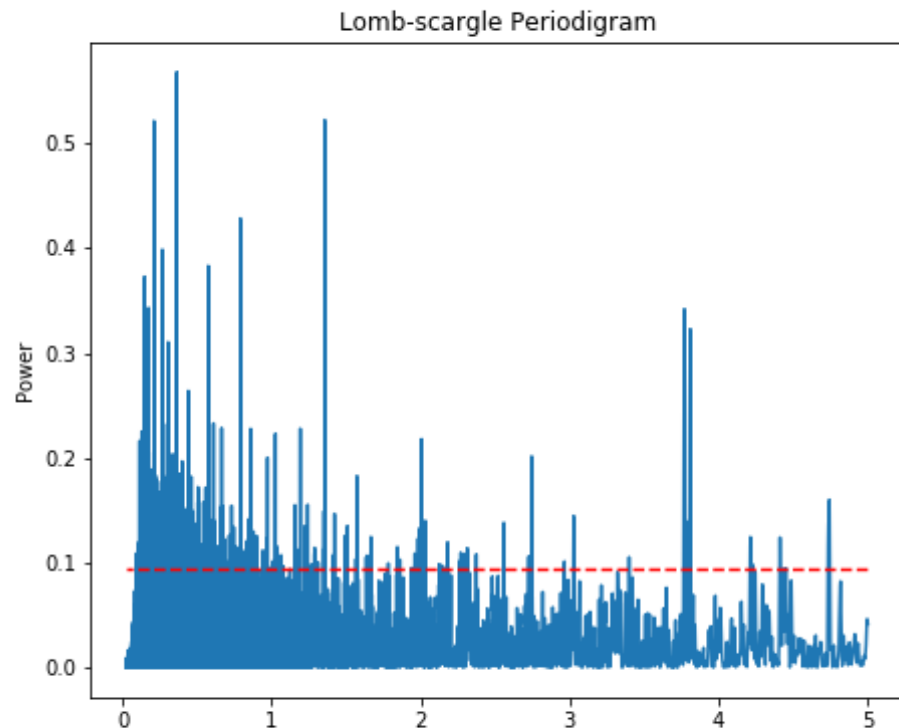
Astropy Example



- Recall our initial example. Astropy can analyse this data set using its class notation

Astropy Example

- Once we plot the periodogram, we can see that there are many significant peaks. We can obtain a periodic signal using the most significant peak ($p=1.9e-40$)



Conclusion

- The Lomb-Scargle periodogram can find periodic behaviour like the FFT, but is useful in different situations:
 - It is mainly used when data points are not evenly spaced
 - It may be used to find periodic data above the Nyquist frequency
- Unlike the FFT, the Lomb-Scargle method introduces error that may be tracked
- Successful use of the method requires selecting a good frequency grid
- Python libraries such as `scipy` and `astropy` provide quick and easy to use tools to apply the method to data