Detection and Removal of Periodic Noise of Kepler/K2 Photometry with Principal Component Analysis

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Abstract
We present a novel method for detrending systematic noise from time series data using Principal Component Analysis (PCA) in Fast Fourier Transforms (FFT). This method is demonstrated on time series data obtained from Campaign 4 of the Kepler K2 mission, as well as two additional objects of interest. Unlike previous detrending techniques that utilize PCA, this method performs the detrending in Fourier space rather than temporal space. The advantage of performing the analysis in frequency space is that the technique is sensitive purely to the periodicity of the unwanted signal and not to its morphological characteristics. This method could improve measurements of low-signal-to-noise photometric features by reducing systematics. We also discuss challenges and limitations associated with this technique.

Kepler & Periodic Signals
The Kepler Space Telescope (pictured left) was designed to detect periodic astrophysical signals such as:
- Exoplanet transits
- Photospheric variability
- Eclipse binaries
but the Kepler catalogue includes periodic systematic noise due to scheduled rolling motion every 6 hours. Spectral analysis tools like Fast Fourier Transforms (FFT) can help analyze not only astrophysical periodicity, but systematics as well.

Left: Sample Kepler lightcurve of an M7.5 brown dwarf and the conjugate square of its Discrete Fourier Transform (DFT), i.e. the power spectrum (PS). The high-amplitude spike is an astrophysical signal caused by photospheric variability. The smaller spike, indicated by the red arrow, is the systematic Kepler roll frequency.

Principal Component Analysis
Principal Component Analysis (PCA), is a dimensionality-reduction technique that transforms the data into a new orthonormal coordinate space, the basis vectors of which are the principal components (PCs). The associated eigenvalues of each PC indicate what fraction of a data point, in our case a vector of flux points, is projected along that axis. The eigenvalues represent how much of the variance present in the data is explained by each PC.
- The components can be sorted by the amount of data variance explained i.e. the first component is the one that alone explains the largest fraction of the variance in the data.)

To detect and characterize systematic periodic noise in a set of synchronously sampled lightcurves, the following steps are performed:
- The power spectrum of each lightcurve is obtained by taking the conjugate square of the Fourier Transform (Oliphant 2006).
- A PCA decomposition was generated using the power spectra as inputs, i.e. a PCA decomposition was generated using the power spectra as inputs, with its prominent peak at 4.09 days.
- The grey shaded regions illustrate the standard deviation along PC1 and PC2 axis (megawatts)

The systematic periodic signatures in our sample of Kepler lightcurves were removed according to Algorithm 1 and some sample results are shown below:

Flares & Ringing Artifacts
Flares are sudden brightening events on a star's photosphere associated with magnetic reconnection events. Discrete Fourier Transforms and principal component analysis produce oscillatory artifacts in the vicinity of discontinuities, a phenomenon known as "ringing". I designed a method that used a 3D Gabor filter (O), optimized by a Markov Chain Monte Carlo (MCMC) routine (2).

Left: Flares on the surface of the star are not periodic whereas the periodic signatures in a light curve are visible. The long-term trend is periodic, but the Kepler catalogue includes periodic systematic noise due to scheduled rolling motion every 6 hours. Spectral analysis tools like Fast Fourier Transforms (FFT) can help analyze not only astrophysical periodicity, but systematics as well.

Left: Left: Results of FFTPCA on the first 1000 transits of HD 189733b. Top Left: Excerpt of a lightcurve showing the planet transit. Top Right: Excerpt of a lightcurve showing the planet transit. The grey shaded regions illustrate the standard deviation along PC1 and PC2 axis (megawatts)

References
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Oliphant, T. E. 2006, A Guide to NumPy, Vol. 1 (Trelgol Publishing USA)