# Frequency Domain Activity Correction (`fdac`): A new Tool in Subtracting Stellar Activity in Planet Searches


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## Introduction

- Finding Earth-like planets around sunlike stars requires detecting **a radial velocity (RV) amplitude of approximately 10 cm/s**. For extreme precision RV surveys (EPRVs), **stellar activity** poses the greatest challenge to terrestrial planet detection. Surface rotation, starspots, oscillations and granulation all produce RV amplitudes on the order of m/s.
- Stellar activity produces periodic and quasiperiodic oscillations that can mimic or hide real planet signals. Disentangling stellar activity and planets requires combining information from RVs and magnetic activity indicators.
- We have developed a frequency-domain activity correction method that uses estimated Fourier coefficients of the activity indicators as explanatory variables for the RV Fourier coefficients. Our method is analogous to a lagged regression in the time domain, but it can be applied to time series with uneven observing cadence.

## `fdac`

The Frequency Domain Activity Correction method, or `fdac`, proceeds as follows:

1. Compute the non-uniform Fourier transforms (NFFT) of the RVs and activity indicator time series
2. Perform a MLR where NFFT of the activity indicators are the explanatory variables of the real and imaginary RV Fourier coefficients:

   $y_{\Re} = \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_n x_{in} + \epsilon$

   $y_{\Im} = \alpha_1 x_{i1} + \alpha_2 x_{i2} + \cdots + \alpha_n x_{in} + \epsilon$

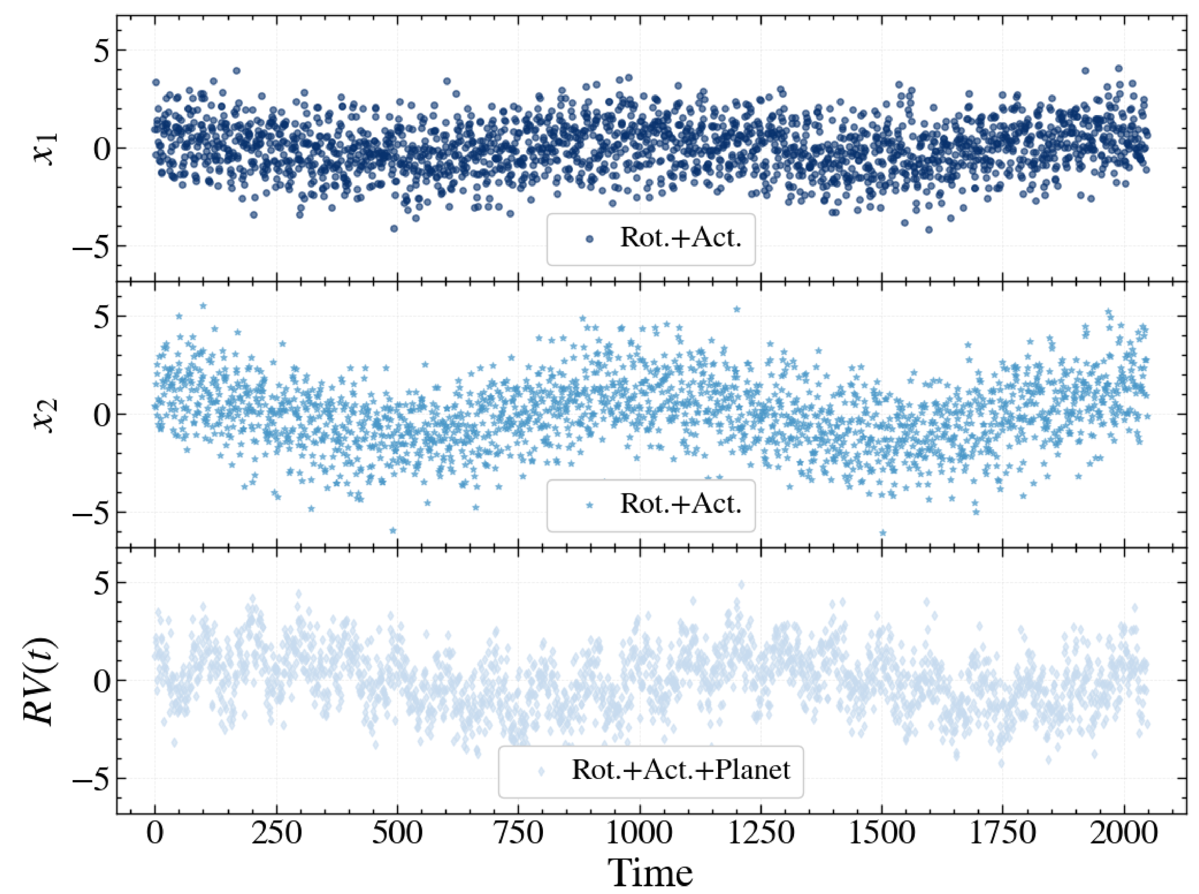
   where $y$ is the predicted NFFT, $x$ is the Fourier coefficient of each activity indicator, $\beta$ and $\alpha$ are the coefficients, $\epsilon$ is the uncertainty in the regression and $n$ is the number of indicators.
3. Inverse NFFT the activity model into the time domain
4. Subtract the time-domain activity model to the RVs to obtain only planet signals.

## Synthetic Data

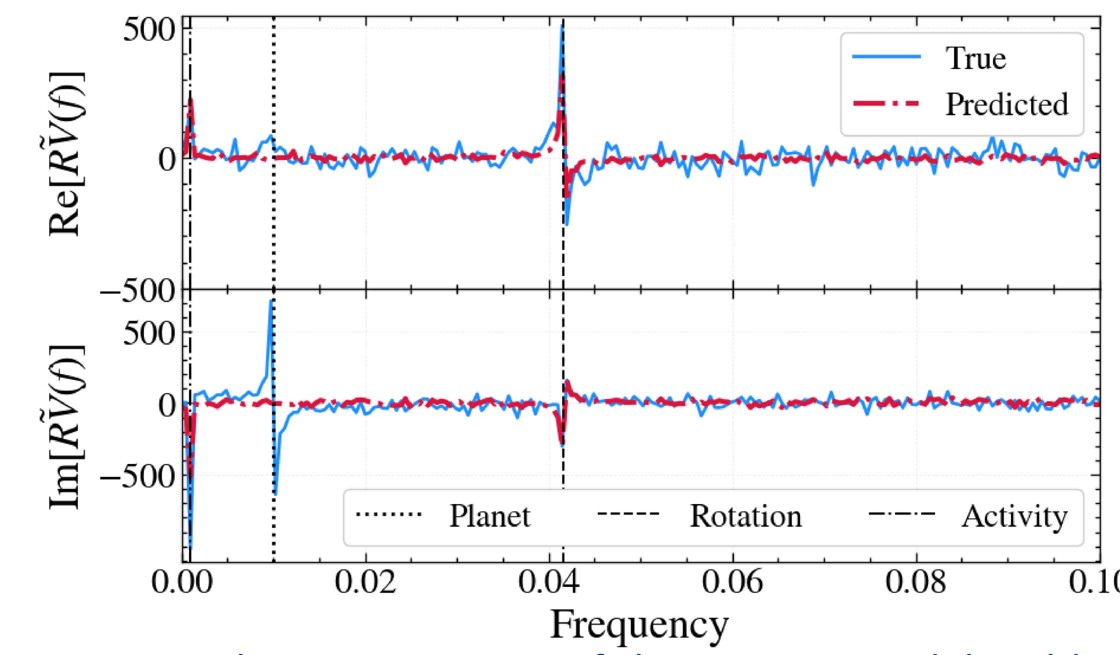
We tested our methodology on a synthetic data set, where we generated a RV time series along with 2 activity indicators. The RV and activity indicators are given by

$$x_1 = \cos(2\pi f_r t) + \cos(2\pi f_a t) + \mathcal{N}(0,1)$$
$$x_2 = \cos(2\pi f_r t) + 1.2\cos(2\pi f_a t) + \mathcal{N}(0,1.2)$$
$$RV = 0.7\sin(2\pi f_r t) + \sin(2\pi f_a t) + \cos(2\pi f_p t) + \mathcal{N}(0,1.2)$$

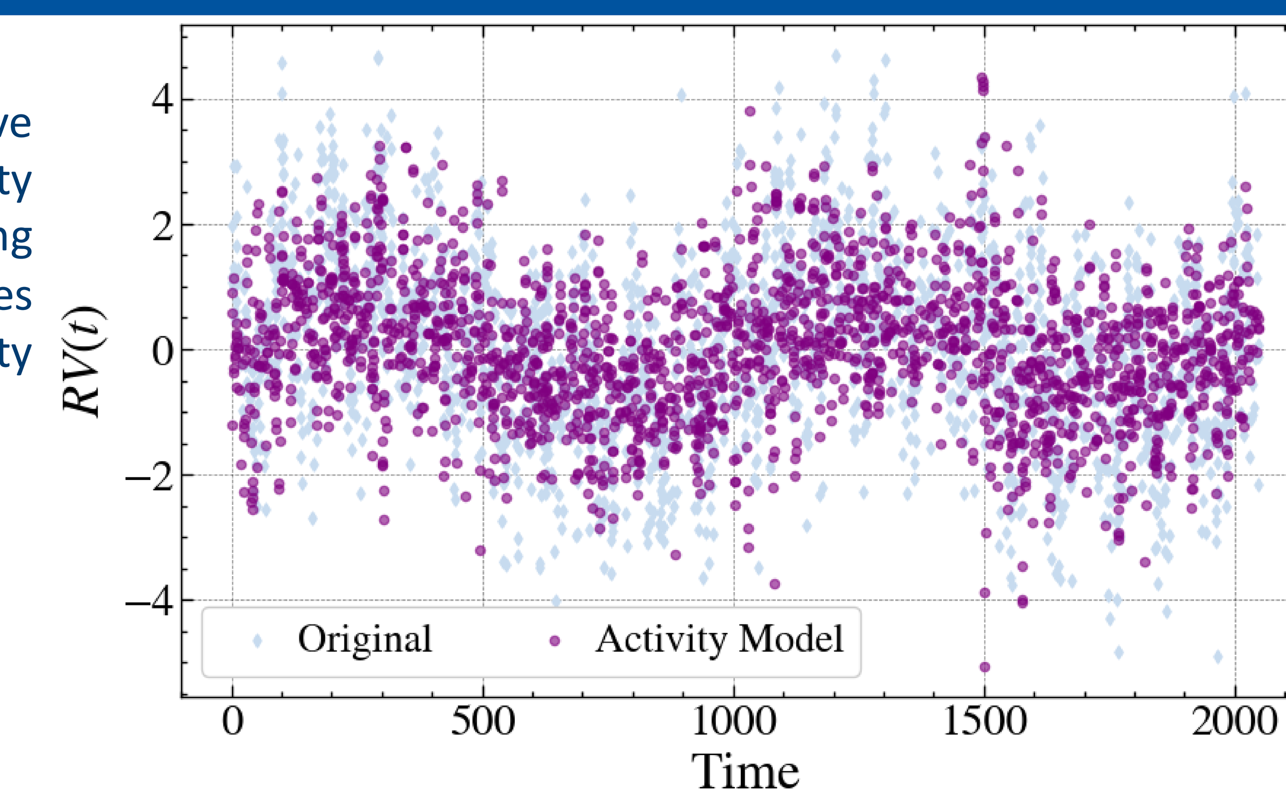
where $f_r$, $f_a$ and $f_p$ are the rotation, activity and planet frequencies respectively, and $\mathcal{N}(0,\sigma)$ simulates noise by producing random numbers drawn from a normal distribution with mean 0 and standard deviation $\sigma$. The time series are plotted below.

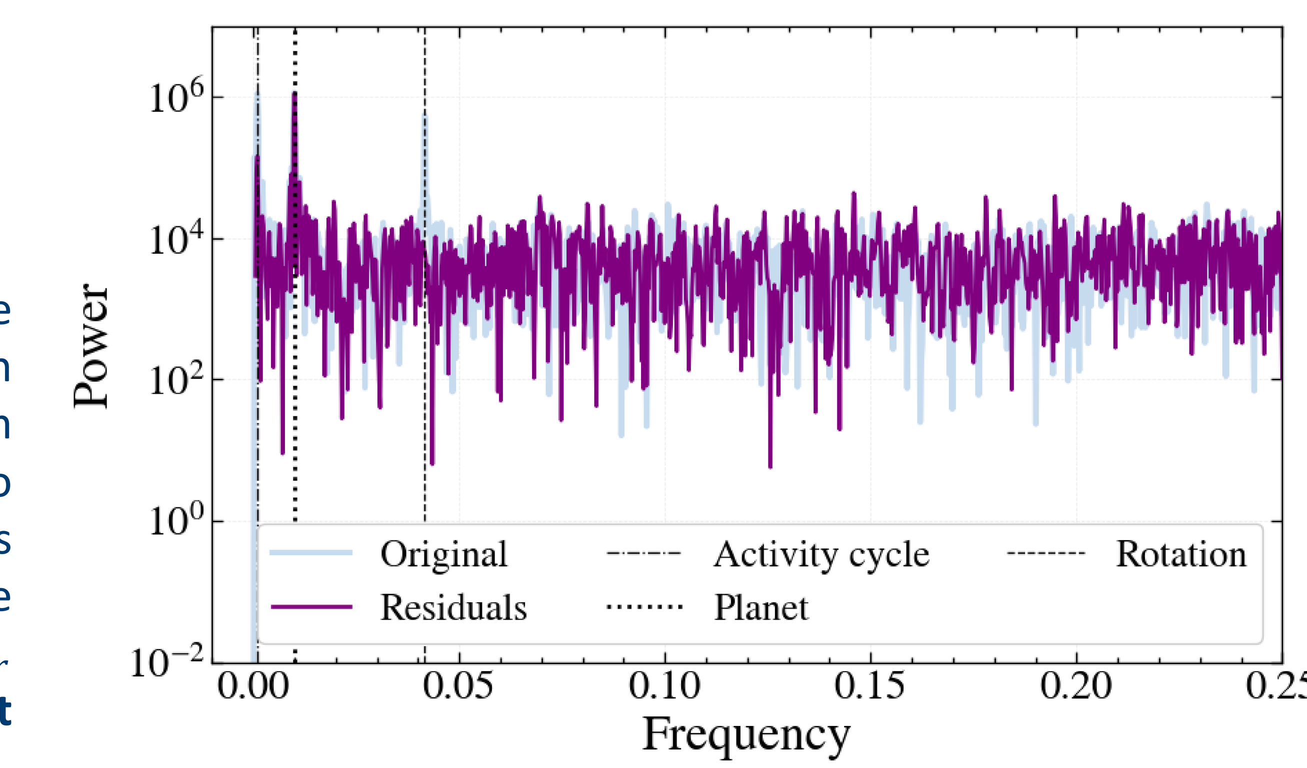



The activity signals are purposefully defined so that they have different amplitudes and phases in the RV and activity indicators. We apply `fdac` to our synthetic data set using Fourier coefficients of $x_1$ and $x_2$ as our explanatory variables for the $RV$ coefficients. The figure below shows the activity model FFT obtained from the MLR.




Computing the inverse NFFT of the activity model yields the time domain model shown on the top-right panel along with the original RV observations. We subtract the model from the RV and compute the periodogram of the residuals to confirm we subtracted the activity signals. The periodograms are shown on the bottom-right panel, highlighting that the residual periodogram has less power at the frequencies $f_r$ and $f_a$, demonstrating **our MLR model was effective at subtracting the stellar signals from the synthetic data.**

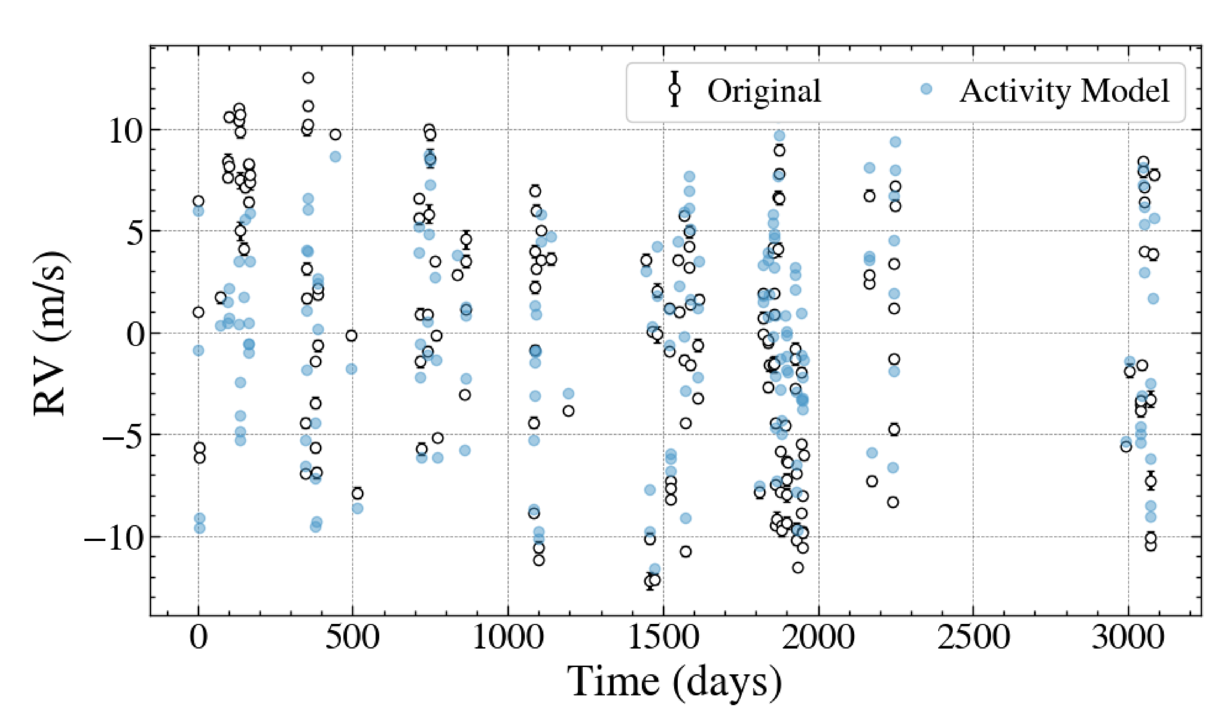


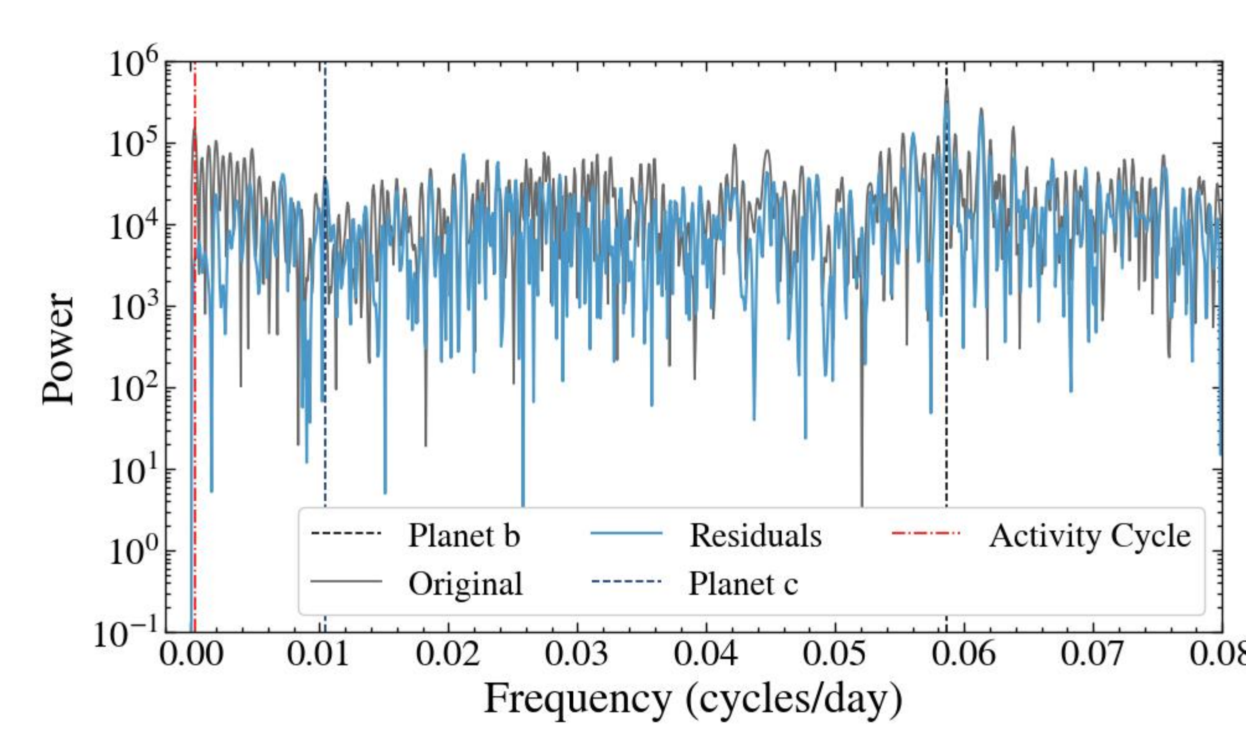




## Archival Data

We analyze the RVs from HD 99492 published by Stalport et al. (2023) taken with the HARPS-N spectrograph. HD 99492 is a K2 Type star with a mass of $0.85 M_{\odot}$. It has two planet detections: Marcy et al. (2005) with **a period of 17.054 days**, and Stalport et al. (2023) with **a period of 95.4 days**. The star's long term activity signal has a period of **≈3000 days**.

We use the activity indicators S-index, Hα, full-width at half max of the cross-correlation function (CCF) and CCF contrast as explanatory variables from the RVs. The left panel below shows the RV measurements along with the activity model in the time domain. From the residual periodogram (right figure), we observe a **significant reduction in the power of the long-term activity signal**, while the power at the periods of planets b and c **remains mostly unchanged**.




## Conclusion

- We developed a new approach to subtract stellar activity from RV observations that consists of using the activity indicator's FFT to perform a MLR on the RV's FFT.
- Testing our technique on synthetic data proved it was able to remove the presence of signals shared between the activity indicators and the RVs.
- We implemented our approach to analyze the archival HARPS-N observations of HD 99492 and we were able to successfully remove the long-term activity signal while keeping the planet signals.
- Future work will explore a wider range of data sets and compare the performance with other methods used to subtract stellar activity.


References:

Marcy G. W., Butler R. P., Vogt S. S., et al., 2005, ApJ, 619, 570.

Stalport, M., Cretignier, M., Udry, S., et al. 2023, A&A 678, A90, doi: 10.1051/0004-6361/202346887.