

Enhancing Periodicity Analysis Accuracy through Phase Fold Amplitude Minimization (PFAM) Technique

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Abstract

In time-series astronomy, periodicity study is one of the most useful tools to understand an astrophysical system. Research papers on periodicity study often show phase-folded plots to emphasize the presence of periodicity. Depending on the quality of the data points, we can use the phase-folded light curves (LCs) to further enhance the accuracy of the observed period. I discuss an amplitude minimization of the phase-folded LC, which can enhance the accuracy of observed periods in astrophysical LCs.

1 Introduction

In time-series astronomy, periodicity study is one of the most useful tools to understand an astrophysical system. The presence of a periodic emission not only tells us about the possible physical activity going on in the system but also enables us to predict future emissions to guide observation projects. There are multiple ways to do a periodicity analysis in a signal, and all of them have some uncertainty associated with the method. I aim to make the periodicity analysis more accurate by using phase folding.

2 Periodicity analysis of a simulated periodic light curve

I simulate a periodic signal with some Gaussian noise along with random sampling to represent a light curve (LC) of an astrophysical source with a periodic emission. The time and amplitude axes have arbitrary units (see Figure 1, top panel). One of the most popular methods for periodicity analysis is the Lomb-Scargle Periodogram (LSP). LSP gives the periodogram of the given signal, from which, we can extract the peak period and its uncertainty. The peak period is the period at which the periodogram power is maximum and the uncertainty is the width at half the relative height of the peak (FWHM). Figure 1 bottom panel shows the LCs periodogram. The detected peak is centered at 2.00 with an uncertainty of 0.40. The reported peak period matches the period of the LC.

The unit of time and period can be internalized with an example. If we are talking about long-term periodicities in blazars, the period would be in the units of years

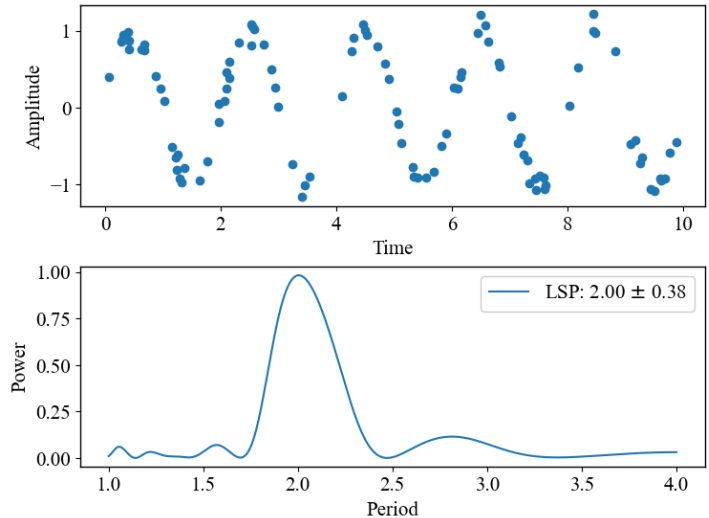


Figure 1: *Top*: Noisy periodic LC with random sampling. *Bottom*: Lomb-Scargle periodogram of the LC.

(PG 1553+113 shows ~ 2 -yr periodicity in its γ -ray LC. e.g., [1]). The uncertainty in the case of this example would be equivalent to 4.8 months. If we are trying to predict future emission patterns and/or propose telescope time, it would be difficult to convince people to let us use their telescope for five months straight. A smaller uncertainty would certainly be useful.

After getting the period and uncertainty from a periodicity study method (does not have to be LSP), one can proceed to fold the LC with that period. This is usually seen being done in periodicity papers to emphasize the existence of the detected period. I am extending this further by folding the LC with a range of period values instead of just the reported peak period, ranging from peak-uncertainty ($2.00 - 0.38$) to peak+uncertainty ($2.00 + 0.38$), and fitting a sinusoidal model function to each of the phase-folded LCs.

In this example, the LC in the top panel is folded with periods in the range of 1.62 to 2.38. Naturally, the value of 2.00 would be the best fit. To show this, in Figure 2 top panel, I have plotted the variance of the sinusoidal fit for different values of the folding period. Here, I have taken the negative logarithm of the variance to emphasize the peak. This plot is then used to narrow down the uncertainty. The FWHM is reduced to 0.17 from 0.38. This $\sim 55\%$ reduction in uncertainty is quite significant.

Going back to the example of the blazar, the uncertainty reduces to ~ 2 months. The bottom panel of Figure 2 shows the LC from Figure 1 (Top panel) folded with a period of 2.00. The best-fit sine curve is overlaid on the folded LC.

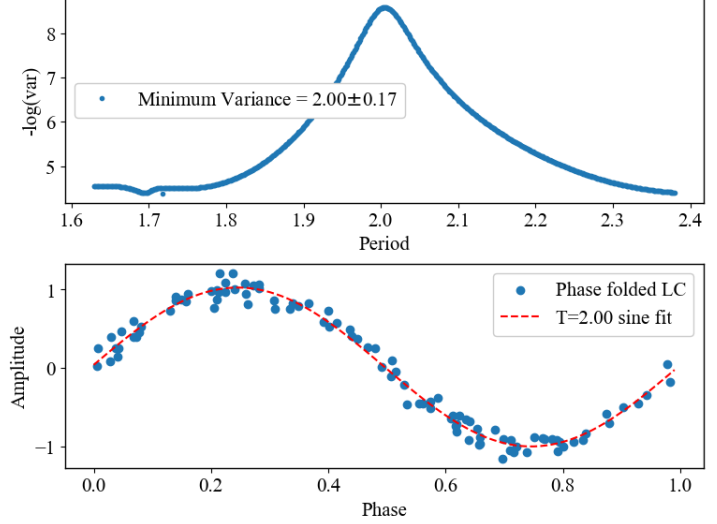
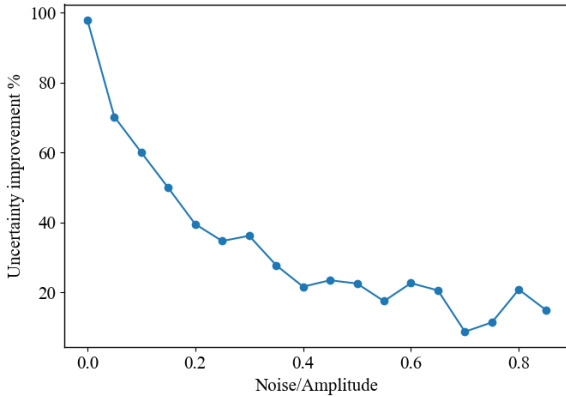
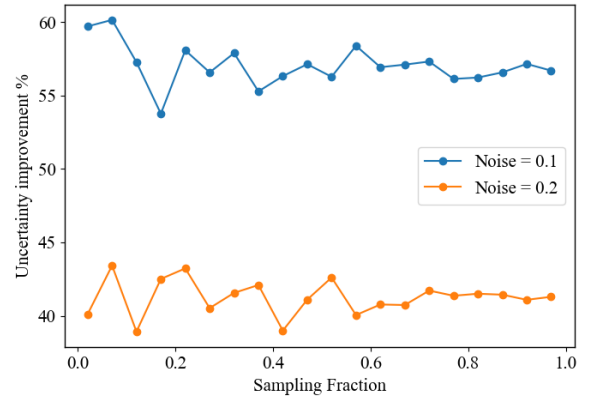


Figure 2: *Top*: Negative logarithm of the variance of sinusoidal fit vs the periods on which the LCs are folded. *Bottom*: Phase-folded LC folded with the best fit period and the best period sine overlaid on top.



(a) Improvement percentage of the uncertainty from LSP to PFAM for various noise levels in the periodic random-sampled signal.



(b) Improvement percentage of the uncertainty from LSP to PFAM for various random-sampling fraction in the periodic signal shown for two different noise levels.

Figure 3: PFAM accuracy-enhancement-limitation study.

I analyzed this reduction in uncertainty for various noise levels and data sampling rates by simulating

multiple periodic signals and performing the PFAM analysis on them. Figure 3a shows as the noise level increases, the improvement in uncertainty decreases sharply. So this method is not very useful if the signal is too noisy but is extremely valuable if the signal has low noise. On the other hand, the data sampling rate has virtually no effect on the improvement of the uncertainty, as seen in Figure 3b, which is a great quality for periodicity analyses, as usually, astrophysical LCs have gaps due to sampling limitations.

Overall, PFAM method to improve the accuracy due to its independence on the sampling rate should be useful for astronomical time-series analyses as long as the signal has a relatively low noise or high signal to noise ratio.

References

- [1] P Peñil, M Ajello, S Buson, A Domínguez, JR Westernacher-Schneider, and J Zrake. Evidence of periodic variability in gamma-ray emitting blazars with fermi-lat. *arXiv preprint arXiv:2211.01894*, 2022.