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The impact of prewhitening in the characterization of pulsating stars observed by space missions

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Abstract

Even when ultraprecise observations are performed by space missions for determining the frequency content of multiperiodic pulsating stars, gaps associated to wrong data acquisition are unavoidable. In these cases, the most extended method in asteroseismology for determining the frequency content consists of an iterative process called prewhitening. The usual assumption is that this method does not alter the original frequency content of the time series. Here we test this assumption by performing frequency analyses of a set of δ Scuti stars from the seismofield of CoRoT satellite. The frequency analyses performed on gapped data show that only the very first frequencies are preserved. It follows from these results that the standard techniques applied in asteroseismology to infer the internal structure of pulsating stars cannot be applied if a reliable filling of the gaps is not performed previously.

1 Introduction

The treatment of gaps may have a significant impact on the frequency analysis performed with Fourier expansion. In particular Pascual-Granado et al. (2015, hereafter PG15) [8] showed that the widely used linear interpolation to fill gaps in the light curves of pulsating stars may introduce spurious frequencies. These authors proposed a new approach to fill gaps by using a method based on an autoregressive, moving-average process, which better preserves the frequency content of the original signal. The distribution and power of the oscillation spectra found with both methods is different in the whole frequency range.

CoRoT had two channels: one for the study of pulsating stars (seismofield) and the other one for exoplanet detection (exofield). The observations in the seismofield are of greater

Run	HD	ID	SpT	mv	log $T_{\rm eff}$ (K)	V	$v \sin i$	Obs.time (d)
IRa01	50844	123	A2	9.1	3,88	1,31	64	57.713
SRc01	174936	7613	A2	8.58	3,9	1,88	170	27.194
SRc01	174966	7528	A3	7.72	3,88	1,95	125	27.197
LRc01	181555	8669	A5 V	7.52	3,85	2,19	200	156.645
LRa01	49434	100	F1 V	5.75	3,86	2,74	-	136.890
LRc02	172189	8170	A2	8.73	3,89	1	-	149.013
SRc02	174532	7655	A2	6.90	3,86	1,38	-	26.239
SRc02	174589	7663	F2 III	6.09	3,85	1,45	100	26.168
LRa02	51722	1022	A5	7.53	3,86	1,13	127	117.375
LRa02	51359	1320	A5	8.50	3,9	0,89	-	117.41
LRa02	50870	546	F0	8.88	3,88	1,67	17	114.413
LRc0506	170699	8301	A2	6,95	3,88	1,49	-	89.282
IRLRa04	GSC00144-03031	21960	A8	10,1	-	-	-	79.133
IRLRa05	41641	5685	A5	7,9	3,882	1,92	28	94.432
SRa05	48784	3619	F0	6,66	3,84	1,87	108	25.305

Table 1: Physical parameters of the selected sample of δ Scuti stars. From left to right: observing run, HD number, CoRoT ID, spectral type, visual magnitude, effective temperature, V magnitude, rotational velocity and observation interval.

precision since the targets are brighter (i.e. lower noise levels) and the cadence is higher (32 secs). We have chosen seismofield light curves of δ Scuti stars in order to evaluate the impact of the gap-filling in the power spectrum. The method for gap filling may have significant impact on asteroseismic studies. In particular for δ Scuti stars, the study of quasi-periodicities is being used to constrain the internal structure of the star (see [5], [11], [7]). These periodicities are highly sensitive to how frequencies are distributed in the periodogram. Any variation due to pre-whitening of light curves filled with methods that not preserve the frequency content might thus induce to different values in these periodicities. Here we want to assess how periodograms are modified depending on the gap-filling method used. It is important to compare the different method currently used (linear filling, no filling and our proposed method ARMA-based filling) in order to better understand the differences in further asteroseismic analysis.

This paper follows this structure: we first describe in Sect.2 the spectral window of CoRoT observations, the sample of stars selected and outline our interpolation method. In Sect.3 we present statistical results from a typical frequency analysis of the gapped light curves, linearly interpolated, and ARMA interpolated light curves. Finally, Sect.4 is devoted to the conclusions.

2 Data set

CoRoT orbital period is about 13.972 d^{-1} [3] and the passing through the South Atlantic Anomaly (SAA) occurs twice a day. Therefore, spurious frequencies in the power spectra of stars observed by CoRoT appear mainly at these frequencies, their multiples and combinations of these frequencies with the frequencies corresponding to the intrinsic variations of the system. In the case of δ Scuti stars the pulsational frequencies are excited in the range between 10-50 d^{-1}. As a consequence the light curves of these stars are affected the most.

Our set consists in 15 stars that were observed in the seismofield of *CoRoT*: 14 δ Scuti stars and 1 γ Dor. The characteristics of these stars are collected in Table 1.

The duty cycle of CoRoT is 90% approx. and the passing through the SAA last about 9 min, therefore, roughly a 10% loss in amplitude is usually expected for periods shorter than 9 min and a minor contribution is expected for periods longer than 18 min (see Appourchaux et al. 2008 [2]). Then, the critical frequency range is from 9 to 18 min but for δ Scuti stars periods no shorter than 18 min are expected. If we accept this assumption a simple linear interpolation should be enough to avoid the contribution of the gaps to the spectral window. This is the correction originally implemented in the pipeline of CoRoT, but though the most frequent gap duration is 9 min, some gaps can last much longer (for example, we have found a gap of about 2 hr in the light curve of HD 170699 and a gap of 5 hr in HD 174589). Then the contribution of these gaps to the spectral window is much greater. Indeed, in PG15 it is demonstrated that the signal is not preserved when linear interpolation is used.

The aim of MIARMA interpolation is to preserve the original frequency content of the signal, thus, avoiding as much as possible the contribution of the spectral window caused by the gaps, which produce a loss in amplitude and phases. While we refer the reader to PG15 for a detailed description of the method, we outline it briefly here.

MIARMA (Method of Interpolation based on ARMA models) is an original algorithm which shares some characteristics with Fahlman & Ulrych (1982) [4] algorithm, i.e. it is based on a weighed forward and backward prediction, but contrary to this, MIARMA make use of ARMA models, which are more parsimonious and can fit optimally the signal. The order of the model is selected through the Akaike Information Criterion [1] and the coefficients of the model are obtained through an optimization algorithm.

The main advantage of MIARMA over other gap-filling methods is that it is aimed to preserve the original frequency content of the time series. This is achieved through a non-analytic approach as the ARMA models are. In contrast to analytic methods, MIARMA guarantees that no spurious information is introduced when filling the gaps.

3 Frequency analysis

In this section we present the results of the frequency analyses of the light curves of δ Scuti stars collected in Table 1. We have made a statistical comparison of the independent frequency components found with SigSpec [10] when the light curves are interpolated with ARMA, linearly, or when the gaps are not filled.

Before the frequency analysis was performed the data were corrected for instrumental drift [3] by performing a linear fit to the light curves and then were analyzed using SIGSPEC. This program has been used widely in asteroseismology literature (for example [6], [9], [5]) and it is based on an iterative sequence of frequency detection, least squares fitting, and a

Star ID	N_{ARMA}	N_{lin}	N_{gap}
GSC00144-03031	3488	2907	2177
HD41641	2300	2350	2850
HD48784	463	425	324
HD49434	1612	1541	2200
HD50844	1746	1657	1489
HD50870	2484	3550	2617
HD51359	2009	2153	2950
HD51722	1750	2800	1650
HD170699	3441	3100	2200
HD172189	1624	1735	2089
HD174532	951	1041	778
HD174589	503	586	251
HD174936	870	915	580
HD174966	645	1016	296
HD181555	2104	2154	2500

Table 2: Number of independent frequencies detected using SigSpec to analyse the light curves observed by CoRoT. First column corresponds to the HD name and columns 2,3,4 corresponds to ARMA interpolated, linearly interpolated and gapped light curves respectively

prewhitening cascade. The iterative sequence stops when a significance limit is reached (by default $sig = 5.0$).

In Fig.1 we show a comparison between the histogram of the frequencies detected in the power spectrum of the linearly interpolated, ARMA interpolated and gapped light curves for two of the stars analyzed: HD 50870 and HD 181555. These are illustrative cases.

In HD 50870 ARMA spectrum is much cleaner than the linearly interpolated. Since the signal is not preserved when linear interpolation is performed the spectral window is much more complex in this case and the convolution between the spectral window and the original frequency content cause that many spurious peaks appear in the power spectrum of the linearly interpolated light curve that are not prewhitened. This is even clearer when comparing with the histogram of the gapped light curve since in that case the histogram profile is more similar to the ARMA one.

On the other side, in HD 181555 the histogram of the linearly and ARMA interpolated light curves are more similar, with a lower density of frequencies per bin in the last case. The density and range of the frequencies detected in the gapped light curve is probably due to an inefficient result of the prewhitening process.

The information of these plots is collected in Table 2 along with the rest of the stars. Notice that the distributions are rather different in each case (ARMA, linear and gapped). No clear tendency or bias is observed. This shows that the effect of the gap-filling is remarkable and can change considerably stellar models and the physics involved.

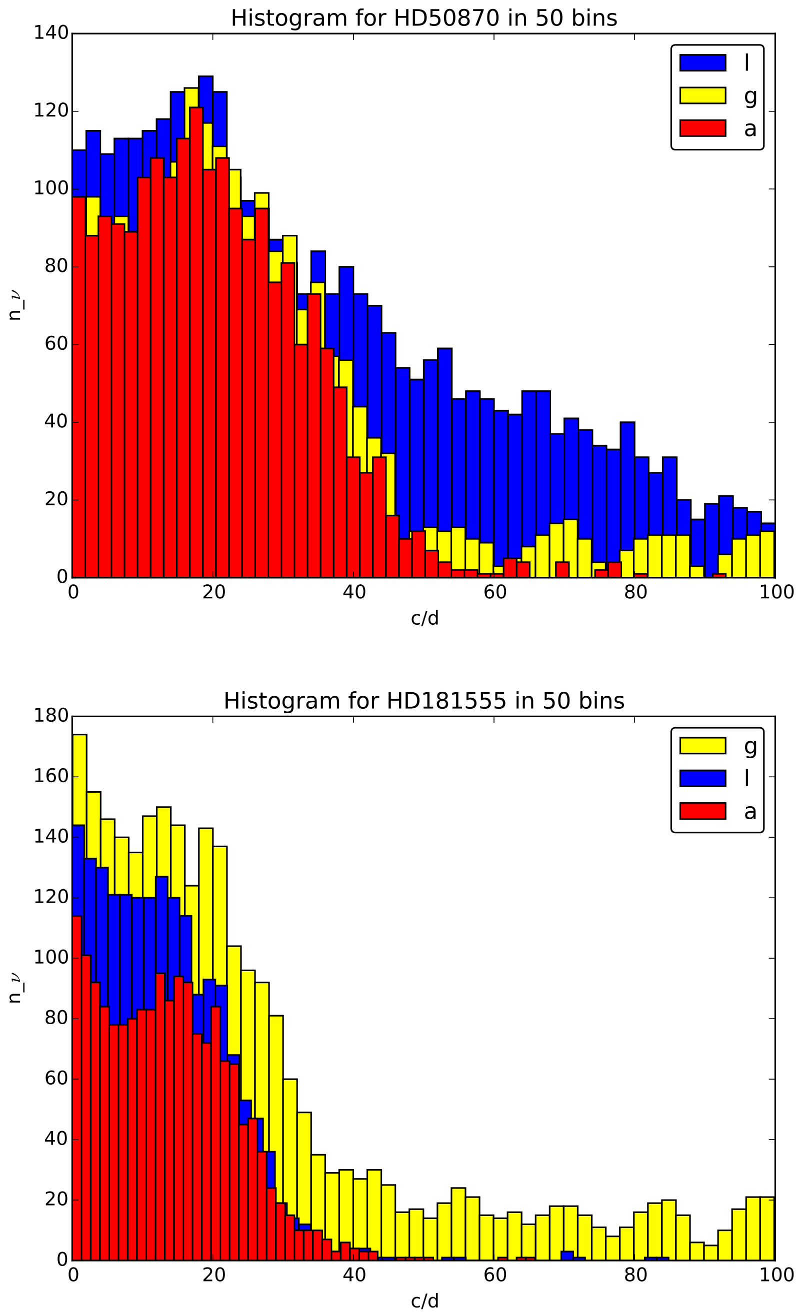

Figure 1: Histogram of the number of independent frequencies detected in the light curves of HD 181555 and HD 50870 star for each set: ARMA (in red), linear (in green), gapped data (in blue). Notice the different distributions.

4 Conclusions

Gaps filled with linear interpolation cause not only a reduced amplitude of the peaks in the power spectrum but also change the original frequency content of the signal introducing spurious peaks that leak the power and change the phases of the original components of the signal.

In PG15 we showed that using a gap-filling method which is aimed to preserve the original frequency content of the time series like MIARMA is essential to obtain an unbiased estimator of the pulsational content of the stars. Here we have emphasized this by using the widely used algorithm SigSpec on a set of 15 δ Scuti stars to perform a frequency analysis of linearly interpolated and ARMA interpolated light curves. We have analyzed gapped light curves using SigSpec in order to test the efficiency of the prewhitening cascade that this program applies to suppress the contribution of the spectral window to the power spectrum. The differences between the results of the analyses show that, at least, for δ Scuti stars is necessary to interpolate to preserve the original frequency content because the prewhitening cascade is not efficient removing the spurious frequencies caused by the gaps.

These results might have a significant impact on asteroseismic studies. We evaluate this in a more detailed paper (Pascual Granado et al., in prep.) with a larger sample of δ Scuti stars observed by the CoRoT satellite

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