Optimizing Weights for the Detection of Stellar Oscillations: Application to $\alpha$ Centauri A and B, and $\beta$ Hydri

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\textbf{Abstract.} We have recently developed a new method for adjusting weights to minimize sidelobes in the spectral window. Here we show the results of applying this method to published two-site velocity observations of three stars ($\alpha$ Cen A, $\alpha$ Cen B and $\beta$ Hyi). Compared to our previous method of minimizing sidelobes, which involved adjusting the weights on a night-by-night basis, we find a significant improvement in frequency resolution. In the case of $\alpha$ Cen A, this should allow the detection of extra oscillation modes in the data.

1. Methods for Optimizing Weights

Using weights has become an integral part of analysing ground-based observations of stellar oscillations. This is due to the significant variations in data quality during a typical observing campaign, especially when two or more telescopes are used. The usual practice is to calculate the weights, $w_i$, for a time series from the measurement uncertainties, $\sigma_i$, according to $w_i = 1/\sigma_i^2$. If weights are not used when calculating the power spectrum, a small fraction of bad data points can dominate and increase the noise floor significantly.

These “raw” weights can then be adjusted to minimize the noise level in the final power spectrum by identifying and revising those uncertainties that are too optimistic, and at the same time rescaling the uncertainties to be in agreement with the actual noise levels in the data. We have previously described the application of this process to velocity observations of solar-like oscillations (Butler et al. 2004; Bedding et al. 2007; Leccia et al. 2007; Arentoft et al. 2008).

These noise-optimized weights can be further adjusted to minimize the sidelobes in the spectral window that arise from daily gaps. This was done on a night-by-night basis for our two-site observations of $\alpha$ Cen A (Bedding et al. 2004), $\alpha$ Cen B (Kjeldsen et al. 2005) and $\beta$ Hyi (Bedding et al. 2007). However, that procedure was not automatic and is therefore impractical for our recent multi-site campaign on Procyon (Arentoft et al. 2008), which involved observations with 11 spectrographs spread over nearly four weeks. We have therefore developed a new method for obtaining the sidelobe-optimized weights (Kjeldsen et al., in prep.).

The new method operates with two timescales. All data segments of a certain length (2 hr, for example) are required to have the same total weight.

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throughout the time series, with the relaxing condition that variations on long time scales (\(>12\) hr, for example) are allowed. The method produces the cleanest possible spectral window in terms of suppressing the sidelobes. In order to test the method, we have applied it to the published data on \(\alpha\) Cen A and B, and \(\beta\) Hyi, allowing a comparison for the three stars of the resulting power spectra and spectral window to those coming from using the original noise- and sidelobe-optimized weights.

The data discussed below originate from three spectrographs: UVES on the ESO VLT at Paranal, Chile; UCLES on the AAT at Siding Spring Observatory in Australia; and HARPS on the 3.6-m ESO telescope at La Silla, Chile.

2. Results

2.1. \(\alpha\) Cen A

The \(\alpha\) Cen A data considered here are those for which the sidelobe-optimization procedure was first developed. The data consist of dual-site observations with UVES and UCLES. Figure 1 shows the time series of weights for three optimization schemes discussed above. The upper panel shows the noise-optimized weights (Butler et al. 2004), the middle panel shows the sidelobe-optimized weights obtained by adjusting on a night-by-night basis (Bedding et al. 2004),
while the lower panel shows the sidelobe-optimized weights obtained with the new method. The UCLES data (black symbols) can be identified in the upper panel as the 5 nights with relatively low weight, as compared to the three nights of UVES data (grey symbols).

As can be seen by comparing the upper two panels in Fig. 1, the sidelobe-optimized spectral window in Bedding et al. (2004) was obtained by reducing the weights of the first two UCLES nights and increasing those of the UCLES data in the period with observations from both telescopes. This resulted in a significant decrease of the sidelobes but it also increased the noise level in the power spectrum because higher weight was given to lower-precision data. There was also a decrease in frequency resolution due to the suppression of the first two nights of observations, effectively shortening the time base of the observations.

Figure 2 shows the spectral windows for the three weighting schemes and Fig. 3 shows the corresponding power spectra. In Table 1 we give the noise levels, effective observing times and frequency resolutions, where the latter are given as the FWHM of the spectral window in power.

Table 1 shows that the two sidelobe-optimization methods result in similar noise levels and both, as expected, have higher noise than that in the noise-optimized power spectrum. However, the new method results in a longer effective observing time and better frequency resolution than the night-by-night sidelobe-optimized weights from Bedding et al. (2004). The improvement can be understood by looking at Fig. 1 where we see that the new sidelobe-optimized weights are more homogeneous and give higher weight to the two first nights, in-
Table 1. Results of applying different weight optimization schemes. Noise levels were measured in the amplitude spectra in the range 4–5 mHz for α Cen A and β Hyi, and at 6–7 mHz for α Cen B.

| Optimization          | Noise Level (cm s\(^{-1}\)) | Effective Obs. Time (days) | FWHM of Spectral Window (µHz) |
|-----------------------|-----------------------------|---------------------------|--------------------------------|
| α Cen A:              |                             |                           |                                |
| noise                 | 2.13                        | 1.30                      | 3.84                           |
| sidelobes (night-by-night) | 3.28                      | 1.74                      | 4.12                           |
| sidelobes (this work) | 3.29                        | 1.99                      | 2.56                           |
| α Cen B:              |                             |                           |                                |
| noise                 | 1.32                        | 1.62                      | 1.82                           |
| sidelobes (night-by-night) | 2.46                      | 2.59                      | 1.44                           |
| sidelobes (this work) | 2.50                        | 2.40                      | 1.34                           |
| β Hyi:                |                             |                           |                                |
| noise                 | 3.45                        | 3.02                      | 1.32                           |
| sidelobes (night-by-night) | 7.61                      | 3.60                      | 1.32                           |
| sidelobes (this work) | 6.64                        | 4.52                      | 1.16                           |

Increasing the effective time base of the observations. The improvement is evident in the spectral window (Fig. 2) and also in the power spectrum itself (Fig. 3), where the bottom panel displays more narrow peaks than the other two panels. In Fig. 4 we show a close-up of the region surrounding the peak at 2572.7 µHz. This peak was listed as both an \(\ell = 0\) and \(\ell = 2\) mode, with the same frequency, in Bedding et al. (2004). Using the new weights, the double-mode nature of this peak is now directly visible in the power spectrum as a result of the increased frequency resolution. Thus, we expect that new scientific results could emerge from a re-analysis of the data using the new weights. This will be investigated in a future paper.

2.2. α Cen B

For this star, the situation is less clear-cut due to the low signal-to-noise (S/N) of the oscillations detected in observations from UVES and UCLES (Kjeldsen et al. 2005). In Fig. 5 we show the three time series of weights and in Fig. 6 the corresponding spectral windows. The power spectra are shown in Fig. 7.

The two sidelobe-optimization methods provide similar results and the new method does not give much improvement over the original sidelobe-optimized weights. It results in slightly lower sidelobes and a slightly better frequency resolution (1.34 vs 1.44 µHz, Table 1), but also in a slightly higher noise level than the night-by-night sidelobe-optimized weights. For both procedures, the frequency resolution is better than with the noise-optimized weights, but the noise levels are almost a factor of two higher. This can be critical for a data set with an already limited S/N, illustrating that the sidelobe-optimization proce-


Figure 3. Power spectrum of $\alpha$ Cen A for the three different weighting schemes.

Figure 4. A close-up of the power spectrum of $\alpha$ Cen A shown Fig. 3.
Figure 5. Time series of the weights for observations of $\alpha$ Cen B
(Kjeldsen et al. 2005) using the three different schemes. Black symbols show
data from UCLES and grey symbols show UVES.

dure is not necessarily optimal for all data-sets, despite the excellent spectral window.

2.3. $\beta$ Hyi

We consider the dual-site observations of $\beta$ Hyi with HARPS and UCLES
published by Bedding et al. (2007). The time series of the weights is shown in
Fig. 8, the spectral windows in Fig. 9 and the power spectra in Fig. 10. The
resulting numbers are again given in Table 1.

Sidelobe optimization increases the noise level greatly as compared to the
noise-optimized weights. This occurs for both versions of sidelobe-optimization,
although less so for the new method. More significantly, whereas the frequency
resolution is not affected by using the night-by-night version of sidelobe op-
timization, the new version gives some improvement (1.16 vs 1.32 $\mu$Hz). The
situation here is similar to the case of $\alpha$ Cen A: the UCLES data are less pre-
cise than the HARPS measurements but span a longer time-base, and the new
method assigns higher weight to the first and (especially) the last nights of the
UCLES data (Fig. 8), increasing the effective observing time.

3. Conclusion

We have applied a new method for calculating sidelobe-optimized weights to
three existing data-sets. The main advantage of this method is the automatic
Figure 6. Spectral window for $\alpha$ Cen B for the three different weighting schemes.

Figure 7. Power spectra of $\alpha$ Cen B for the three different weighting schemes.
Figure 8. Time series of the weights for observations of $\beta$ Hyi (Bedding et al. 2007) using the three different schemes. Black symbols show data from UCLES and grey symbols show HARPS.

Figure 9. Spectral window for $\beta$ Hyi for the three different weighting schemes.
convergence to the solution that provides the cleanest possible spectral window. For the three stars, α Cen A, B and β Hyi, the new weights discussed here improve the data sets in terms of frequency resolution and/or noise levels as compared to the published versions of the weights. For α Cen A, the improvement is at a level where new scientific results could emerge. The method has thus been tested successfully and can be applied with confidence to the new multi-site Procyon data presented by Arentoft et al. (2008).

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