Abstract
The activity-related variations in the solar acoustic frequencies have been known for 30 years. However, the importance of the different contributions is still not well established. With this in mind, we developed an empirical model to estimate the spot-induced frequency shifts. We also propose a new observable to investigate the short- and mid-term variations of the frequency shifts.

Model frequency shifts
Spot-induced frequency shifts, $\delta \nu_{\text{spots}}$:

- spots affect the propagation of acoustic waves
- that perturbation can be expressed by the phase difference, $\Delta \delta$, between the wave solutions inside the spot and outside
- we assume that $\Delta \delta$ can be approximated by a characteristic phase difference, $\Delta \delta_{\text{ch}}$, equal for all spots
- we derived a relation for the frequency shifts, $\delta \nu$, following the approach by Cunha & Gough (2000)

$$\frac{\delta \nu_{\text{im}} (t)}{\nu_{\text{im}} (t)} \propto -\Delta \delta_{\text{ch}} \sum_{i=1}^{N(t)} \left( P_l^m (\cos \theta_i) \right)^2 \delta A_i$$

* $l$ and $m$: mode angular degree and azimuthal order
* $P_l^m$: Legendre polynomials
* $N(t)$: number of spots at a given time $t$
* $\theta_i$ and $A_i$: colatitude and area of a given spot $i$

Total model frequency shifts, $\delta \nu_{\text{model}}$:

$$\delta \nu_{\text{model}} = \delta \nu_{\text{global}} + \delta \nu_{\text{spots}}$$

$\delta \nu_{\text{global}}$ = global component varying on the 11-yr time scale, related to the overall magnetic field

Conclusions

- the sunspot contribution to the observed frequency shifts is roughly 30%
- the component responsible for the loss of correlation between $\Delta \delta \nu_{\text{obs}}$ and $\Delta A_T$ should vary in short time-scales being modulated by the mid-term (quasi-biennial) signal
- there is a mid-term contribution to $\delta \nu_{\text{obs}}$ that is not accounted in the sunspot model

References: