Accurate Mapping of the Torsional Oscillations: a Trade-Off Study between Time Resolution and Mode Characterization Precision

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Abstract. One salient result of global helioseismology is the mapping of the so-called torsional oscillations below the solar surface. These subsurface flows are inferred by inverting rotational frequency splitting sets of global modes. These flows extent down to a depth of at least 0.8 R, and are likely associated with the activity cycle of our star. To better understand the mechanisms that drive the solar cycle we need to accurately map these flows, and characterize precisely their penetration depth and their temporal behavior.

We present a study of the spatial (depth and co-latitude) and temporal variations of the solar rotation rate associated with the torsional oscillation based on state-of-the-art mode fitting of time series of various lengths of MDI observations, namely 1456-, 728-, 364- and 182-day long time series. Such approach allows us to better estimate how much significant information can be extracted from the different time spans and hence trade-off time resolution for precision in the inverted profiles resulting from the different mode sets.

1. Introduction

Helioseismic inferences have confirmed that the differential rotation observed at the surface persists throughout the convection zone [9], [6], [2], [4]. The outer radiative zone ($0.3 < r/R_\odot < 0.7$) appears to rotate approximately as a solid body at an almost constant rate (≈ 430 nHz), whereas the innermost core ($0.19 < r/R_\odot < 0.3$) rotates slightly faster than the rest of the radiative region. At the base of the convection zone, a shear layer —known as the tachocline— separates the region of differential rotation throughout the convection zone from the one with rigid rotation in the radiative zone. Finally, there is a subsurface shear layer between the fastest-rotating layer at about $0.95R_\odot$ and the surface. The rotation profile of the sun is not constant: the time-varying component of the rotation is referred to as the torsional oscillations at the surface, while we see hints of variations at the base of the convection zone, both being likely related to the solar activity cycle. However we still need to constrain the rotation profile and fully analyze the nature of the torsional oscillations. Theories about the mechanisms that drive the solar rotation and its variations remain to be tightly constrained by improved helioseismic inversion results. Better inversions mean not only improved inversion methodologies but especially improved rotational splittings.

We have used frequency sets resulting from fitting MDI time-series of various lengths in order to study the effect of the length of the time series on the characterization of the torsional oscillations. Fitting epochs of various lengths leads to averaging these epochs at the power spectrum level. This allows fitting spectra with higher signal to noise ratio and thus extracting the most significant information, as well as leading to values consistent among the different sets. For this purpose, rotational splitting sets were derived from fitting MDI 1456-, 728-, 364- and 182-day long time series [6], [7]. By comparison, the MDI pipeline data are estimated using 72-day long time-series, while the GONG pipeline data are estimated using 108-day long time-series. These standard products were also inverted for the work presented here. An iterative inversion methodology [3] was applied to the data sets to infer the rotation rate in the solar interior.

2. Results and conclusions

All the splitting sets calculated from time series of a given length were inverted and a temporal mean of the rotation rate was computed. The departure of the set of rotation profiles from the temporal mean is plotted as a function of time in order to visualize the torsional oscillations. These torsional oscillations are presented in Fig. 1 at the solar surface as a function of co-latitude and in Fig. 2 at a co-latitude of 20 degrees as a function of depth. While overall the same pattern is observed at the surface, *i.e.* the migration towards the equator of the faster-than-average rotation band, the results are far from identical, in particular at high co-latitudes (see Fig. 1). One of the reasons for the discrepancy might come from the fact that the MDI- and GONG-pipeline sets contain few low-azimuthal order modes (those more sensitive to high co-latitudes), since we only consider modes that are fitted at all epochs. By contrast, the data derived from the MDI 1456-, 728-, 364- and 182-day long time series do not suffer such significant mode set attrition.

The reduction of the mode sets for the MDI- and GONG- pipeline data does not only affect low-m modes, but also low-degree modes. As a result, the temporal behavior of the rotation profile in the inner part of the convection zone and the radiative zone is less resolved by the pipeline data. Hence, the torsional oscillations signal seems to dissolve with depth (below $0.8R_{\odot}$) for the GONG and MDI-pipeline results (see Fig. 2), whereas it remains strong down to approximately the tachocline for the Korzennik's MDI data, in particular for MDI 728- and 364-day long series. The rotation profiles obtained from the inversion of MDI 1456- and 728-day long series show intriguing results below the tachocline: it seems that the time averaging process does not completely remove the oscillatory pattern in the radiative zone that might be seen in the inversions of MDI 182- and 364-day long series; some faster-than-average and slower-than-average rotation bands remain strong below the tachocline. The significance of these results will be tested in future works through the inversion of artificial data sets and spatial resolution analysis of the inversions.

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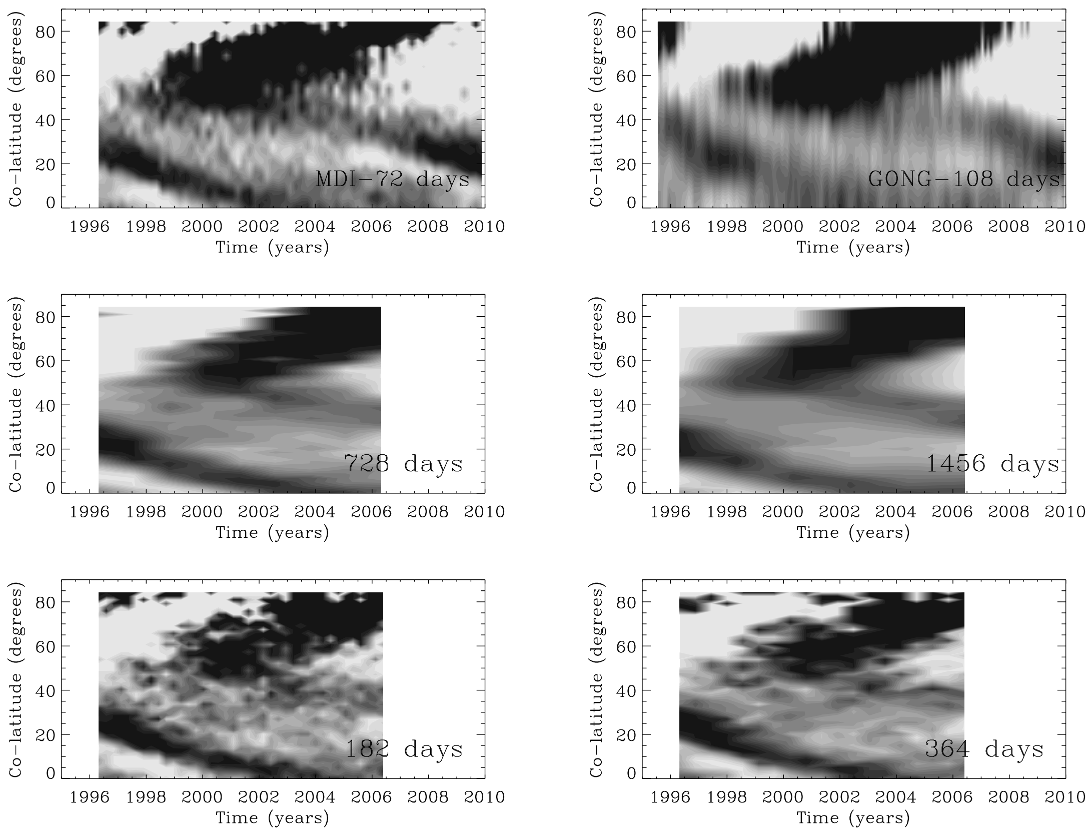

Figure 1. Rotation profile departure from a temporal mean as a function of co-latitude at $r = R_\odot$, inverted from six data sets, namely 108-day long GONG-pipeline, 72-day long MDI-pipeline, 182-day long MDI-Korzennik, 364-day long MDI-Korzennik, 728-day long MDI-Korzennik, and 1456-day long MDI-Korzennik.

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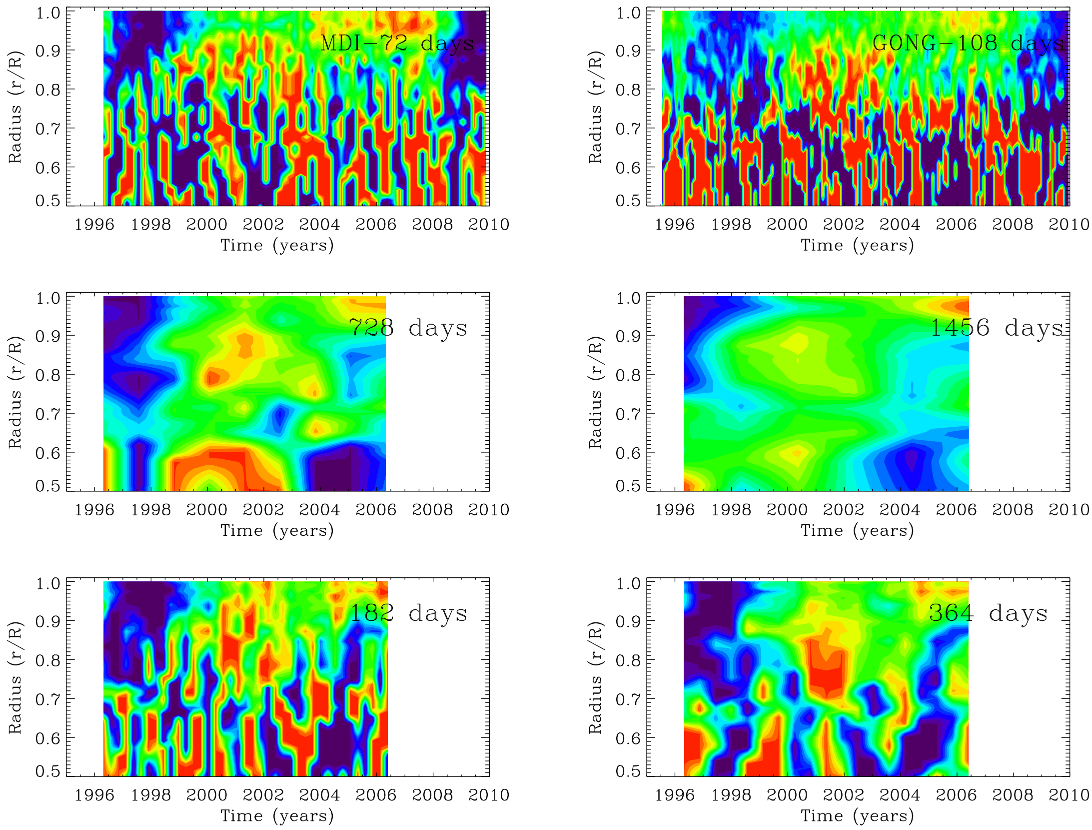

Figure 2. Rotation profile departure from a temporal mean as a function of depth at $\phi = 20$, inverted from six data sets, namely 108-day long GONG-pipeline, 72-day long MDI-pipeline, 182-day long MDI-Korzennik, 364-day long MDI-Korzennik, 728-day long MDI-Korzennik, and 1456-day long MDI-Korzennik.