Long-Term Datasets for the Understanding
of Solar and Stellar Magnetic Cycles
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Un-interrupted Sun-as-a-star Helioseismic Observations over Multiple Solar Cycles

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Abstract. We analyze Sun-as-a-star observations spanning over solar cycles 22 – 24 from the ground-based network BiSON and solar cycles 23 – 24 collected by the space-based VIRGO and GOLF instruments on board the *SoHO* satellite. Using simultaneous observations from all three instruments, our analysis suggests that the structural and magnetic changes responsible for modifying the frequencies remained comparable between cycle 23 and cycle 24 but differ from cycle 22. Thus we infer that the magnetic layer of the Sun has become thinner since the beginning of cycle 23 and continues during the current cycle.

Keywords. Sun: activity, Sun: helioseismology, Sun: oscillations, Sun: interior

1. Introduction

Long-term observations of solar activity clearly show the variable nature of Sun's magnetism. These observations, e.g. in the form of sunspot counts and groups, exist for the past several centuries and provide large databases to understand the long-term as well as short-term trends in solar variability. In addition, a database of cosmogenic isotope variations is also available for a much longer period providing long-term records of solar geomagnetic activity. However, such records to understand the variations below the surface are only a few decades old and consist of the inferences obtained from the resonant p-mode oscillations. The frequencies of oscillating modes are modified by the mechanical properties of the layers through which the waves traverse, and provide insights for the study of structural and dynamical changes occurring in the Sun's interior. These frequencies vary with the changing level of magnetic activity and display strong correlations with the measures of solar activity (e.g., Broomhall & Nakariakov 2015, Jain *et al.* 2009, Salabert *et al.* 2015, and references therein). Various oscillation data sets are now available which cover a wide range of modes and are sensitive to different layers of the interior. In this paper, however, we will only discuss low-degree modes that penetrate the solar core. It may be noted that the low-degree modes are generally better determined from the Sun-as-a-star observations which implies that the observables e.g. velocity, intensity etc. are integrated over the entire disk.

2. Un-interrupted Sun-as-a-star Observations

Since the discovery of solar oscillations, there have been several instruments which provide data for the Sun-as-a-star observations. In this study, we use following data sets which cover the period of more than a solar cycle.

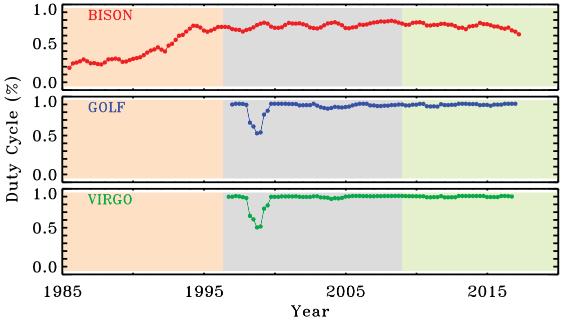

Figure 1. Duty cycle of the data sets used in this study.

Birmingham Solar Oscillation Network (BiSON): The BiSON instruments use the technique of resonance scattering spectroscopy to make Doppler observations in the K line at 769.9 nm. The network has been operational since 1981 and its six-site configuration was completed in 1992 (Davies *et al.* 2014, Hale *et al.* 2016).

Global Oscillations at Low Frequencies (GOLF): GOLF onboard *SoHO* measures the radial velocity Doppler shift, integrated over the solar surface, in the Na D1 and D2 Fraunhofer lines at 589.6 and 589.0 nm, respectively (Gabriel *et al.* 1995, García *et al.* 2005). It has been providing high-quality data since April 1996 covering the solar activity cycles 23 and 24 with two short gaps in 1998-99 due to the temporary loss of the *SoHO* spacecraft.

Variability of Irradiance and Gravity Oscillations (VIRGO): VIRGO onboard *SoHO* is composed of three Sun photometers (SPM) at 402 nm (Blue), 500 nm (Green) and 862 nm (Red) and provides integrated intensities in these three wavelengths (Fröhlich *et al.* 1996). The coverage of VIRGO data is similar to GOLF.

3. Analysis and results

We analyzed 32 years of continuous observations starting from Jan 1, 1985 from the BiSON network and 21 years of observations from the GOLF and VIRGO instruments. The frequency tables are computed for 365 day subsets that overlapped by 91.25 days. It is well known that long-term data often suffer from the degradation of instruments and/or other observing environments. Thus, to minimize the bias, the start and end times in the time series have been selected so that where contemporaneous data exist the subsets are temporally aligned. The BiSON data span over three solar cycles (22 – 24) and constitute 128 data sets while GOLF and VIRGO data cover cycles 23 – 24 and constitute 81 and 82 data sets, respectively. Duty cycles for all instruments are plotted in Figure 1. It is observed that the duty cycles for GOLF and VIRGO are above 96% with a strong dip during the loss of *SoHO*. However, in case of BiSON, the duty cycle increased with time due to the deployment of more sites, reached a maximum value of 84% and remained consistent after the network was completed.

The frequency shifts, $\delta\nu$, were calculated for $\ell = 0 - 3$ modes in the frequency range of 1860 μHz $\leqslant \nu <$ 4250 μHz. Using the BiSON data until the rising phase of cycle 24, Basu *et al.* (2012) suggested that the changes in the Sun affecting the oscillation frequencies in cycle 23 were localized mainly to layer above about $0.996R_{Sun}$. Following their suggestion and the evidence that different frequencies have maximum sensitivity in different layers near the surface, we further carried out our analysis in four different frequency ranges. These ranges are: low ($1860 \leqslant \nu < 2400$ μHz), mid ($2400 \leqslant \nu < 2920$

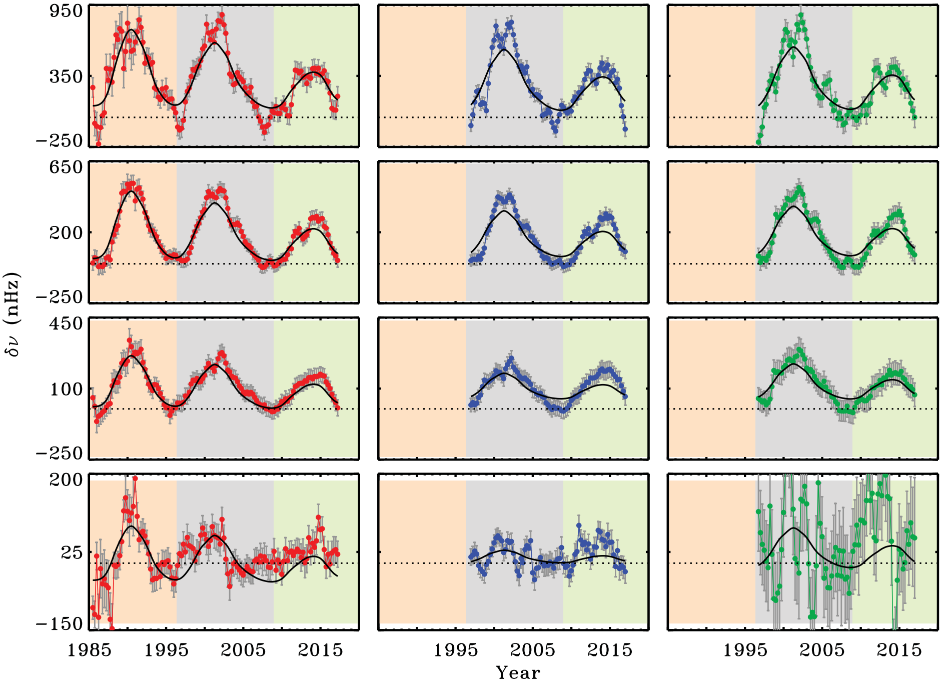

Figure 2. Average frequency shifts observed by BiSON (left), GOLF (middle) and VIRGO (right) as a function of time for four frequency ranges; Top: $3450 \leqslant \nu < 4250$ μHz, 2nd from the top: $2920 \leqslant \nu < 3450$ μHz, 3rd from the top: $2400 \leqslant \nu < 2920$ μHz, and bottom: $1860 \leqslant \nu < 2400$ μHz. The symbols in each panel show the average shift in frequency while the uncertainties are shown by grey. The solid black line depicts the scaled 10.7 cm radio flux variation.

μHz), high ($2920 \leqslant \nu < 3450$ μHz) and very high ($3450 \leqslant \nu < 4250$ μHz). While modes in the low frequency range have maximum sensitive to $0.996R_{Sun}$, those in the high frequency range are sensitive to $0.999R_{Sun}$.

We display the temporal variation of $\delta\nu$ in all four frequency bands in Figure 2. It is evident that the VIRGO shifts in the low frequency range are noisier than the other two instruments. We also note that the uncertainties in the BiSON shifts in the rising phase of cycle 22 are significantly higher probably due to the low duty cycle as shown in Figure 1. In addition, the uncertainties in the shifts obtained from modes in the highest frequency range is larger than mid and high frequency ranges indicating that the goodness of fit reduces with the increase of frequencies after certain frequency.This is because the widths of the peaks in the power spectrum increases so substantially that it is difficult to constrain the frequency. Furthermore, the amplitude (or S/N) is lower here.

The scaled variation of F10.7 cm radio flux (Tapping 2013) averaged over the same epochs that were used to calculate frequency shifts is over plotted in Figure 2. The correlation between frequency shifts and radio flux is tested by calculating the Pearson's linear correlation (see Table 1). Comparing correlation coefficients between cycles 22, 23 and 24 for BiSON, we find that there is a small change in mid and high frequency ranges while it decreased significantly in cycles 23 and 24 in low frequency range. This implies that the layer sensed by the low-frequency modes has changed with time and this change occurred either during the declining phase of cycle 22 or later. It should be further noted that the correlation for the low-frequency modes is about 30 to 40 percent lower than the other frequency ranges. In order to precisely determine the period of this change, a detailed phasewise correlation is required and will be presented in a future publication.

Table 1. Correlation statistics between frequency shifts and 10.7 cm radio flux.

	BiSON					**GOLF**					**VIRGO**				
Frequency Range(μHz)	**Solar Cycle**					**Solar Cycle**					**Solar Cycle**				
	22	23	24	22–23	23–24	22	23	24	22–23	23–24	22	23	24	22–23	23–24
$1860 \leqslant \nu < 2400$	0.79	0.58	0.63	0.66	0.56	-	0.59	0.65	-	0.54	-	0.41	0.19	-	0.59
$2400 \leqslant \nu < 2920$	0.95	0.96	0.96	0.94	0.95	-	0.94	0.95	-	0.95	-	0.95	0.94	-	0.94
$2920 \leqslant \nu < 3450$	0.97	0.97	0.97	0.97	0.97	-	0.96	0.97	-	0.96	-	0.96	0.97	-	0.96
$3450 \leqslant \nu < 4250$	0.87	0.96	0.95	0.92	0.86	-	0.95	0.92	-	0.94	-	0.95	0.94	-	0.94

Unfortunately, GOLF and VIRGO instruments became operational at the beginning of cycle 23 and cannot be used to confirm the results obtained from the BiSON data for cycle 22. However, the agreement between results for cycle 23 and 24 from all the three instruments confirm that the Sun has gone through the near-surface structural changes in last few solar cycles and continues during the present cycle.

4. Summary

Long-term simultaneous Sun-as-a-star observations from three instruments illustrate that structural and magnetic changes responsible for the frequency shifts remained comparable between cycle 23 and cycle 24, and are different from cycle 22. We have also demonstrated that the magnetic layer of the Sun has become thinner in last two solar cycles. However, these low-degree modes also penetrate deeper however and there are differences when the modes confined to the convection zone are analyzed. For example, the minimum sensed by these modes happened around the same time as in the solar activity indicators while the low-degree modes sensed minimum about a year earlier (Jain *et al.* 2011, Salabert *et al.* 2009, Tripathy *et al.* 2010). Thus, these findings advocate the need of a long-term data base of solar oscillations (similar to solar activity) in order to understand the variability of different layers in the solar interior and its link to the surface magnetic activity.

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