Towards solar activity maximum 24 as seen by GOLF and VIRGO/SPM instruments

R. A. García¹, D. Salabert², S. Mathur³,⁴, C. Régulo⁵,⁶, J. Ballot⁷,⁸, G.R. Davies¹,⁹, A. Jiménez⁵,⁶, R. Simoniello¹

¹ Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot; CEA, IRFU, SAp, F-91191, Gif-sur-Yvette, France
² Laboratoire Lagrange, UMR7293, Université de Nice Sophia-Antipolis, CNRS, Observatoire de la Côte d’Azur, Bd. de l’Observatoire, 06304 Nice, France
³ High Altitude Observatory, 3080 Center Green Drive, Boulder, CO, 80302 USA
⁴ Space Science Institute, 4750 Walnut Street, Suite 205, Boulder, Colorado 80301 USA
⁵ Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain
⁶ Dept. de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain
⁷ CNRS, Institut de Recherche en Astrophysique et Planétologie, 14 avenue Edouard Belin, 31400 Toulouse, France
⁸ Université de Toulouse, UPS-OMP, IRAP, 31400 Toulouse, France
⁹ School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

E-mail: rgarcia@cea.fr, salabert@oca.eu, smathur@SpaceScience.org, crr@iac.es, Jerome.ballot@irap.omp.eu, davies@bison.ph.bham.ac.uk, ajm@iac.es, Rosaria.Simoniello@cea.fr

Abstract. All p-mode parameters vary with time as a response to the changes induced by the cyclic behavior of solar magnetic activity. After the unusual long solar-activity minimum between cycles 23 and 24 —where the p-mode parameters have shown a different behavior than the surface magnetic proxies— we analyze the temporal variation of low-degree p-mode parameters measured by GOLF (in velocity) and VIRGO (in intensity) Sun-as-a-star instruments on board SoHO. We compare our results with other activity proxies.

1. Introduction
GOLF and VIRGO/SPM instruments have been observing since 1996 and are well suited to the study of low-degree, solar-acoustic mode characteristics [1]. Thanks to their high-quality observations, we are able to measure all the p-mode properties with very high precision not previously attainable, including mode asymmetries [2]. Moreover, the temporal variations of the p-mode parameters during cycle 23 can be studied [3, 4, 5]. The unexpected long activity minimum between cycles 23 and 24 [6] demonstrates that the physical processes governing the magnetic activity in the Sun are not yet well understood.

2. Observations and Data Analysis
We analyzed observations collected by the space-based GOLF [7] and VIRGO [8] instruments onboard SoHO. A total of 6000 days were analyzed covering nearly 16.5 years between 1996 and 2012. These datasets were split into contiguous 365-day subseries, with a one-fourth overlap. The
power spectrum of each subseries was fitted to extract the mode parameters using a standard likelihood maximization function (power spectrum with a $\chi^2$ with 2 d.o.f. statistics). Each mode component was parameterized using an asymmetric Lorentzian profile [9]. The temporal variations of the frequency shifts were defined as the difference between reference values (taken as the average over 1996-1997) and the parameters of the corresponding modes observed at different dates. Subseries with duty cycles less than 90% (around the SoHO vacation) were not taken into account for this analysis. The weighted averages over the central part of the 5-min oscillation power –from 2200 to 3400 $\mu$Hz– of the temporal variations of the mode parameters were then calculated. Mean values of daily measurements of the 10.7-cm radio flux were used as a proxy of the solar surface activity. Linear regressions were performed between the temporal variations of the mode parameters and the radio flux using independent points only.

3. Frequency Variations of Individual Low-Degree p Modes
In Fig. 1 we show the average temporal variations of the l=0,1, and 2 p-mode frequencies observed by GOLF and VIRGO following [10]. The 11-year solar cycle is clearly visible with a quasi-biennial superimposed, originally described by [11], and fully discussed in [12, 13]. Mode frequency shifts are anticorrelated with their amplitude and no significant temporal variations have been found in the rotational splittings, in agreement with [14, 15].

The Pearson linear correlation coefficients and the probabilities of having no correlation between the temporal variations of the p-mode parameters measured in the photometric VIRGO data and the 10.7-cm radio flux are given in Table 1. These variations are linked to the cyclic changes of Sun’s magnetic activity.

Table 1. Pearson correlation coefficients ($r$) and probabilities of having no correlation ($P_{r=0}$) between the temporal variations of the mode frequencies ($\langle \Delta \nu \rangle$), heights ($\langle \Delta h \rangle$), linewidths ($\langle \Delta \gamma \rangle$), and asymmetries ($\langle \Delta b \rangle$) measured from the blue channel VIRGO data and the corresponding $F_{10.7}$ radio flux used as a magnetic activity proxy.

|       | $\langle \Delta \nu \rangle$ | $\langle \Delta h \rangle$ | $\langle \Delta \gamma \rangle$ | $\langle \Delta b \rangle$ |
|-------|-------------------------------|-----------------------------|-------------------------------|-------------------------------|
| $r$   | 0.97                          | 0.94                        | 0.93                          | 0.69                          |
| $P_{r=0}$ | 4.76 x 10^{-9}               | 3.56 x 10^{-7}             | 1.10 x 10^{-6}                | 1.26 x 10^{-3}                |

4. Mode Excitation and Damping with Solar Activity
The temporal variations of the mode amplitudes, $<\Delta h>$, and linewidths, $<\Delta \gamma>$, are shown in Fig. 2 computed using the three VIRGO/SPM channels. The Pearson linear correlation coefficients with the 10.7-cm radio flux are given in Table 1. Note that due to absolute calibration problems and the changes of the observing wings [16], the GOLF amplitudes and linewidths are not exploitable in this analysis. A proper calibration is currently underway.

In Fig. 3, we show the variations of $A_{max}$ [17] as it is usually done in asteroseismology to track down activity cycles [18]. The maximum power at $\nu_{max}$ was computed by fitting a Gaussian on the p-mode envelope, as explained in [19], and converted to bolometric amplitude following [20]. The results are comparable to the average of the individual mode amplitudes as shown in Fig.2a.
5. Variation of Asymmetry

In Fig. 4, the temporal variations of the peak asymmetry $<\Delta b>$ of the modes observed by GOLF and VIRGO/SPM are shown. Due to the change in the GOLF observing configuration between

![Figure 1](image1)

**Figure 1.** Left panel: Temporal variations of low-degree modes as described in the text; GOLF (black) and VIRGO (blue). The solid lines correspond to the scaled radio flux. Right panel: Frequency shifts as a function of the radio flux at 10.7 cm.

![Figure 2](image2)

**Figure 2.** Average of the amplitudes (a,b) and linewidths (c,d) of the modes $l = 0, 1$ and 2 obtained using the three independent VIRGO channels: blue, green, and red as a function of time (left panels) and the radio flux (right panels). The solid lines correspond to the scaled radio flux.

![Figure 3](image3)

**Figure 3.** Temporal variation of $A_{max}$ using the averaged three VIRGO/SPM channels as explained in the text.
the blue and the red wing [16], the variations (gradient) with the cycle are different (see Fig.4b). Pearson correlation coefficients of the VIRGO/SPM asymmetries are included in Table 1.

Figure 4. Average of the mode asymmetries computed using GOLF (a,b) and VIRGO/SPM (c,d) data as a function of time (left panels) and radio flux (right panels). The solid lines correspond to the scaled radio flux.

6. Solar Activity Proxy with GOLF and VIRGO/SPM

By correcting the raw VIRGO/SPM averaged data with the algorithms developed to process Kepler light curves [21], we are able to measure the temporal evolution of the rotation signature produced by the sunspots crossing the visible solar disk. Indeed standard VIRGO/SPM time series are filtered from periods longer than around 3 days. With this new procedure, we can keep longer periods up to 140 days. Therefore, we are not sensitive to changes in the faculae during the cycle. This effect produces a smooth increase of the solar brightness correlated with the cycle that cannot be disentangled from the ageing of the phototubes that we have filtered out.

We performed a time-frequency analysis of the time series using a Morlet wavelet [22]. It consists of calculating the correlation between a sliding mother wavelet and the time series where we change the period of the wavelet. This produces the wavelet power spectrum (Fig. 5, top panel).

The projection of the wavelet power spectrum in the range 6 to 60 days on the time axis (Fig. 5, bottom panel), provides information of the temporal evolution of the magnetic structures crossing the visible solar disk at the frequencies of the rotation and its first harmonics. We use here a conservative approach by selecting a wide range between 6 and 60 days. This is equivalent to computing a moving variance of the time series. However, our methodology has the advantage of being only sensitive to structures that have a periodicity around the rotation period. Therefore, we obtain a magnetic activity proxy linked to magnetic spots. This methodology could be used to track magnetic activity cycles in other stars.

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Figure 5. Top: Wavelet power spectrum of VIRGO/SPM computed using [22, 19]. Bottom: Projection onto the time axis as explained in the text. The dotted vertical lines correspond to the starting of the SoHO summer vacation period and the end of the winter vacation period. The blue line corresponds to the radio flux used as a proxy of the magnetic activity cycle averaged over 10 days.

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References
[1] Toutain T, Appourchaux T, Baudin F et al. 1997 Solar Phys. 175 311
[2] Thiery S, Boumier P, Gabriel A H et al. 2000 Astron. & Astrophys. 355 743
[3] Gelly B, Lazrek M, Grec G, et al. 2002 Astron. & Astrophys. 394 285
[4] Jiménez-Reyes S J, García R A, Jiménez A, Chaplin W J 2003 Astrophys. J. 595 446
[5] Jiménez-Reyes S J, Chaplin W J, Elsworth Y et al. 2007 Astrophys. J. 654 1135
[6] Salabert D, García R A, Pallé P L, Jiménez-Reyes S J 2009, Astron. & Astroph. 504 L1
[7] Gabriel A H, Grec G, Charra J et al. 1995 Solar Phys. 162 61
[8] Frohlich C, Romero J, Roth H et al. 1995 Solar Phys. 162 101
[9] Nigam R & Kosovichev A G 1998 Astrophys. J. 505 L51
[10] Salabert D, Chaplin W J, Elsworth Y, New R, Verner G A 2008, Astron. & Astrophys. 463 1181
[11] Broomhall A M, Chaplin W J, Elsworth Y, Fletcher S T, New R 2009 Astrophys. J. 700 162
[12] Fletcher S T, Broomhall A M, Salabert D et al. 2010 Astrophys. J. 718 19
[13] Simoniello R, Finsterle W, Salabert D et al. 2012 Astron. & Astroph. 539 135
[14] García R A, Mathur S, Ballot J, et al. 2008 Solar Phys. 251 119
[15] Broomhall A M, Salabert D, Chaplin W J et al. 2012 MNRAS 422 3564
[16] García R A, Turck-Chièze S, Bournier P et al. 2005 Astron. & Astroph. 442 385
[17] Kjeldsen H, Bedding T R, Arentoft T et al. 2008 Astrophys. J. 682 1370
[18] García R A, Mathur S, Salabert D et al. 2010 Science 329 1032
[19] Mathur S, García R A, Régulo C et al. 2010 Astron. & Astroph. 511 46
[20] Michel E, Baglin A, Auvergne M et al. 2008 Science 322 558
[21] García R A, Hekker S, Stello D, et al. MNRAS 414 L6
[22] Torrence C & Compo G P 1998 BAMS 79 61