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On the nature of the current GOLF p-mode signal

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Abstract. The GOLF experiment on board SOHO is designed to measure global oscillations of the disk-integrated sunlight with high sensitivity and with long term stability. The GOLF data is thus ideally suited for both the study of the p-mode spectrum and to address the search for gravity modes. Due to their occasional malfunction the project decided to stop the rotating polarizing elements at an optimum place in order to maintain a precise sequence of measurements with the highest possible duty cycle. This action means that subsequently GOLF only measures two monochromatic intensities I_b^+ and I_b^- on the blue wing of the sodium doublet. In this work we investigate the nature of these signals separately and in combinations. Our method is to study the temporal relative phase relations between the low degree ($\ell \leq 3$) p-mode signals derived from data sets obtained from simultaneous observations, both from other SOHO instruments (GOLF and SOI) and from Mark– I, the Tenerife station of the ground-based BiSON network. It is found that these signals are "almost" pure velocity signals. A simple model indicates that a contamination of a pure intensity-like signal of 14% amplitude would fully explain the true nature of the current GOLF signal. Moreover, it is found that the ratios, defined for other instruments (Mark–I, SOI and, by extension BiSON and IRIS), also have exactly the same nature as the GOLF ratio.

Key words: Sun: general – Sun: interior – Sun: oscillations

1. Introduction

The GOLF spectrophotometer is one of the three instruments specifically designed for helioseismic investigation on board SOHO. A particular objective of GOLF was to reach high sensitivity and stability for the oscillations' power spectrum over the frequency range 10^{-7} to 10^{-2} Hz. The measurement of the disk-integrated photospheric line-of-sight velocity by means of a resonant scattering technique applied to the Na D1 and D2 lines, allows a precise determination of the spectral characteristics of low degree solar p-modes (Lazrek et al. 1997). In addition, its performance in terms of stability and sensitivity, permits a deep investigation of the low frequency part of the spectrum ($\nu < 500$ μHz), where solar gravity modes are expected to be found. SOHO was successfully launched on December 2 1995 and the GOLF door was definitively opened on January 1996. The instrument became fully operational by the end of the month. During the following months the occasional malfunction of GOLF's rotating polarizing elements led to the decision to halt the rotation at a position providing optimal line wing purity, so that truly non-stop observations began by mid April 1996. Since then, GOLF has been continuously and satisfactorily operating although in an unforeseen mode. The effect of this mode on data quality has been less adverse than initially expected. Although the scientific results provided up to now by GOLF (Lazrek et al 1997; Turck-Chièze et al. 1997; Régulo et al. 1998) corroborates the above statement, concerns about the nature of the signal and its calibration in this mode need to be studied and understood in view of the fact that the planned methods cannot be used.

The primary signal now consists of monochromatic photometric measurements of light scattered out of very narrow bands ($\sim$ 25 mÅ) on the left wings of the sodium doublet lines. These lines can retain their overall intensity shapes and shift due to the motion of the solar atmosphere – this is a pure velocity signal. These lines can remain fixed in wavelength centroid but undergo an alteration in their intensity at the scattering wavelengths – this is a pure intensity signal. The actual solar line can vary due to both effects in some relative proportion. We seek to determine the degree of contamination of the velocity signal by the intensity signal. While this question is of great interest for all components of the GOLF signal in all spectral bands, the results of this paper apply directly to those signals generated by coherent $p-$mode oscillations and our conclusions depend on the eigenmode structure of these modes. Other signals such as those generated by convective phenomena could have a differ-

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ent balance between the velocity and intensity contributions to the GOLF signal.

This work, which is a continuation of a preliminary analysis performed by Régulo et al. (1998), describes our study of the nature of GOLF signal utilizing a comparison of the temporal phase of the acoustic p-modes in different data sets. This oscillation parameter is very sensitive to the balance between intensity and velocity in a way which is largely independent of calibration questions. From general theoretical considerations for an oscillation which produces a pure wavelength shift of a given absorption line, intensities measured on opposite wings of the line should be perfectly anti-correlated; that is, a fluctuation of similar amplitude (depending on the slopes of the wings) will be obtained but 180° out of phase. In contrast, for an oscillation which produces an intensity fluctuation of the whole line the signals on the opposite wings will be in phase. For the actual case of the solar atmosphere, it is well known that coherent fluctuations of intensity and velocity will be out of phase by a quantity that depends on the thermodynamic properties of the atmosphere. In a part of the atmosphere where the oscillation is expected to be non-adiabatic the relative phase angle will lie between 90 and 180 degrees, – the limits for the adiabatic and isothermal cases respectively. From ground and space observations this phase shift has been measured (see Schrijver et al. 1991 and references therein) to be between -120 and -130° (in the sense Intensity-Velocity), when low degree ($\ell < 4$) p-modes between 2.5 and 4.2 mHz are studied. In the following section we compare different simultaneous data sets coming from the GOLF instrument during those periods where different measurements were simultaneously available, and during other periods we compare the GOLF data to observations from two other spectrophotometers: SOI and Mark–I.

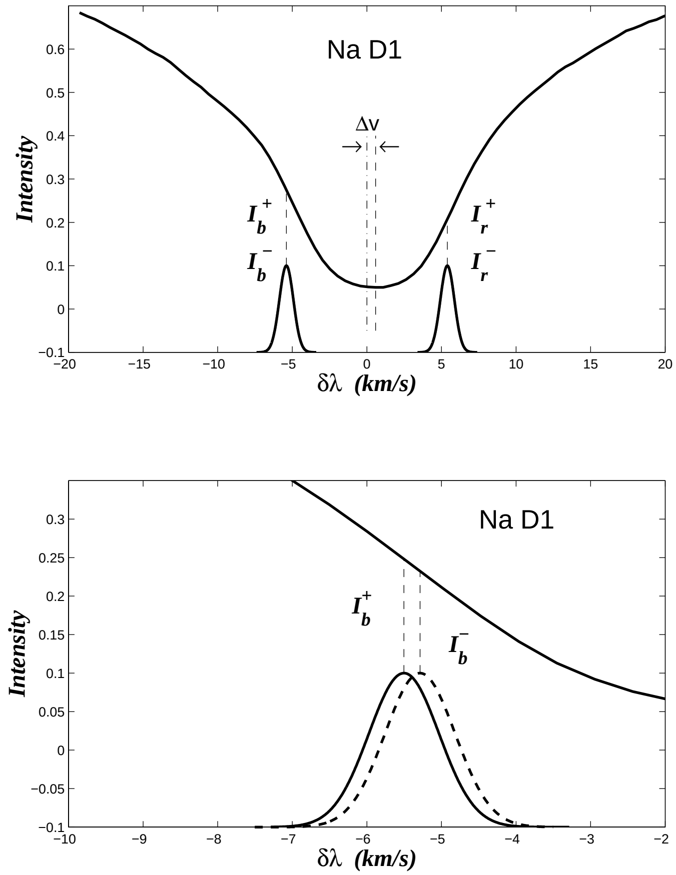


Fig. 1. Illustration of the operation modes *B* (*top*) and *C* (*bottom*) on GOLF instrument on one of the components of the Na doublet and for a given displacement ΔV of the solar spectral line. The velocity position of the Blue and Red components corresponds to the center of the 1.2 Km/s region scanned by them. For *Mode C* only the region around the operating point is shown.

2. Observational data sets definition and preparation

Basically we have used data from three instruments: two on board SOHO (GOLF and SOI) and another one on ground (Mark– I), all three having independent timing and all three providing simultaneous observations for different spectral lines.

2.1. GOLF data

The GOLF instrument was designed to provide disk-integrated measurements of the solar radial velocity and also the longitudinal component of the global magnetic field by means of resonant scattering of solar sodium doublet radiation (D1 at λ 5 896 and D2 at λ 5 890 Å) in a vapour cell. The scattering wavelengths of the sodium atoms in the cell are split into two longitudinal Zeeman components by a strong permanent magnet surrounding the cell, thus monitoring the two wings of the solar sodium doublet (I_b and I_r). Each wing is alternatively selected with appropriate polarization of the incoming light. Moreover, the magnetic field at the cell is produced by both the permanent magnetic ($\sim$ 5 000 Gauss) and a modulating by a small electromagnet ($\sim$ $\pm$ 100 Gauss). Consequently two close intensities on both wings (I_b^+, I_b^- and I_r^+, I_r^-) can be measured, enabling the determination of the wings' slopes at the operating points. Finally, GOLF had the capability of performing the described measurements for two different states of circular polarization of the incoming solar light, and was thus sensitive to the longitudinal component of the mean solar magnetic field.

In the nominal mode of operation (Gabriel et al. 1997), *Mode A*, a total of 16 intensity measurements at intervals of 5 s (with scattered photons being counted for 4 seconds out of the available 5) completed one measurement cycle in which all moving elements (polarizer and quarter-wave plate), responsible for the different polarization analysis of incoming light, return to their initial position. Out of these sixteen intensities the first eight measurements are essentially equal, in the optical sense, to the second eight. Unfortunately, the rotating mechanism for the quarter-wave plate first showed a malfunction and was thus stopped. The instrument moved then to another mode of operation: *Mode B*, in which two sets, with four measurements each are now a complete cycle (see Fig. 1 top). Some weeks afterwards the remaining rotating mechanism (the one with the polarizer element responsible for switching between the red and blue wings) exhibited the same kind of malfunction. The decision to stop the second rotation mechanism was taken at the beginning of April 1996, and the instrument was commanded to perform operations which moved the polarizer to an optimum place were it has remained. In this mode the GOLF system observes the blue wings of the Na doublet without any moving device. This decision enables GOLF to achieve a nearly 100% duty cycle (as no moving parts are now in the instrument) which yields the "cleanest" spectrum of the solar oscillations possible; however, potential information on the red wing measurement is lost. Therefore, GOLF instrument from April 11 up to present has operated in *Mode C*, that is with two sequential measurements on the blue wing: I_b^+ and I_b^-. The two operating modes, *B* and *C*, are illustrated in Fig. 1 for one of the components of the sodium doublet. Data taken with *Mode A* include some long interruptions due to the commissioning of GOLF itself and also the SOHO spacecraft. Data taken in *Mode B* have a larger measurement duty cycle, $\sim$ 96%, although they were obtained also during SOHO commissioning phase.

In summary, the signals derived from GOLF data that will be used in further analysis and the mode of operation in which they were obtained are:

$$\mathrm{R}_{GOLF} = F(v)\left(\frac{I_b^{\pm} - I_r^{\pm}}{I_b^{\pm} + I_r^{\pm}}\right) - V_{\ell s}, \quad \text{Mode B} \qquad (1)$$

$$\mathrm{X}_b = f_b(v)\left(\frac{1/2(\mathrm{I}_b^+ + \mathrm{I}_b^-)}{\langle \mathrm{I}_b^+ - \mathrm{I}_b^- \rangle}\right) - V_{\ell s}, \ \text{Modes B, C} \qquad (2)$$

$$\mathrm{X}_r = f_r(v)\left(\frac{1/2(\mathrm{I}_r^+ + \mathrm{I}_r^-)}{\langle \mathrm{I}_r^+ - \mathrm{I}_r^- \rangle}\right) - V_{\ell s}, \quad \text{Mode B} \qquad (3)$$

$$\Delta\mathrm{S} = g^{\pm}(v)\left(\frac{\mathrm{I}_b^{\pm} - \mathrm{I}_0^{\pm}}{\mathrm{I}_0^{\pm}}\right), \quad \text{Mode C} \qquad (4)$$

where $\langle \quad \rangle$ stands for a low pass filter to avoid magnifying the high frequency noise in the slope measurement and the $\pm$ superscripts denote the phase of the magnetic modulation. The velocity functions that appear on the right hand side of the above equations ($F(v), f_b(v), f_r(v), g^{\pm}(v)$), correspond to the calculated sensitivities which allow conversion of intensities into velocities and $V_{\ell s}$ is the known line of sight velocity Sun$-$SOHO. Moreover, $\mathrm{I}_{\mathrm{b,r}}^{\pm}$ represent the instantaneous intensities measured in both wings at different places ($+$ and $-$) and $\mathrm{I}_0^{\pm}$ the corresponding filtered reference intensity values derived from a low pass filter having a width of approximately 30 days.

In all cases, prior to their use in the above equations the raw intensities have been corrected for different effects: in the photomultipliers (dead time, aging and high voltage), a modulation due the sun–spacecraft radial distance variation and instrumental parameters (temperatures of the stem of the sodium cell and of the photocatodes). The above magnitudes, calibrated into velocity units, represent different approaches to what could be a true Doppler shift due to the solar oscillations. Although the aim of this work is not the detailed description of the calibration techniques (which will be done in a forthcoming paper by Ulrich et al. 1998), a very brief description of the guidelines is given here for clarity. Also in Gabriel et al.(1997) some general ideas are given and in García (1996) a full study of calibration techniques applied to GOLF numerically simulated data can also be found.

The calibration procedure is quasi-standard in the case of *Mode B* operation; the similarity with the existing ground-based instrumentation (IRIS and BiSON) allows us to apply techniques similar to those already described in the literature (Pallé et al. 1993, Elsworth et al. 1995). Furthermore the continuous measurement of the local slopes of each wing and the use of this information for the calibration was previously tested on ground observations (Boumier et al. 1994). From Fig. 1, the passband intensities formed in the blue and red wings of the line (after correction for detector dark counts), are combined to form a normalized ratio (right side of Eq. (1)) which is proportional to the sampled velocity via an appropriate non-linear calibration function. Therefore, the original ratios can be adequately linearized (see for instance Pallé et al. 1993) and then compared with the known line of sight velocity (orbital, halo and gravitational redshift components) to calibrate them. Finally the difference between the two velocities yields directly the velocity residuals, R_{GOLF} which is the signal that contains the required information. By using this method, the 30 days, from February 19 to March 19 1996, of GOLF data available in *Mode B* were calibrated to obtain the corresponding time series. Just for calibration purposes, the red wing signal, X_r, has been multiplied by -1 in order to convert it to a signal which is positively correlated with $V_{\ell s}$ as is the blue signal; a positive velocity shift corresponds to an increase of the blue signal counting value and to a decrease for the red one (see Fig. 1 top). In addition, a small asymmetry of the mechanical cycle was apparent in the data. This effect is due to the fact that two consecutive measurements taken in an identical optical configuration did not correspond to equivalent mechanical positions of the polarizers so that a fixed velocity shift is introduced between two consecutive measurements of the quantities X_b, X_r and R_{GOLF}. Consequently this asymmetry produces a very high frequency noise. Because this effect shows up as an even-odd difference, it was easily identified and has been properly corrected even though it is clearly a second order effect as far as phase determinations are concerned.

In *Mode C* the polarizer elements no longer rotate, so only the small magnetic modulation on the blue wing of the line is available (see Fig. 1 bottom), and the two quantities I_b^- and I_b^+ are gathered at intervals of 5 s each. The calibration of the blue wing measurement is not obvious so that different approaches have been considered to properly calibrate the measurements and obtain the corresponding residuals: a) use the known line of sight velocity as a reference (X_b); b) use low frequency filters and assume a known velocity scale (since this method is a direct rescaling of the intensity fluctuations to match ground-based velocities, no calibration equation was given above) and c) through the use of the magnetic modulation and the varying sun-spacecraft velocity derive the line profile and model the observations, (ΔS).

As it can be seen in the formulae above, while only one magnitude is available in *Mode C*, there is a 30 day period in *Mode B*, in which not only X_b but also X_r and R_{GOLF} are simultaneously available. This period is thus of great interest to us because it permits us to investigate the nature of the single-wing measurements by comparing this parameter with the velocity parameter derived from the standard ratio. Additionally, in *Mode C* two different definitions and ways of calibration were performed so that the reliability and consistency of both procedures can be studied in the p-mode frequency band by comparing p-mode phases.

2.2. Mark–I data

This spectrophotometer has been operated since 1976, from 1984 onwards in a continuous way, at the Observatorio del Teide (Tenerife) and proved to be already one of the most successful instruments in the Helioseismology field (Harvey1995) and it currently is acting as a node of the BiSON network. It uses the same physical principle as GOLF but with different polarization elements and uses a different solar absorption line (Potassium KI 7 699 Å). This difference is not a problem as it has already been proved that, using calibrated ratios obtained simultaneously at Sodium and Potassium wavelengths, the mean phase difference between solar p-modes of low degree ($\ell \leq 3$) is zero within errors (Pallé et al. 1992), which is what can be expected from the standing wave behavior. Therefore this data set is useful for comparison with the GOLF signal. Ideally we would like to compare simultaneous measurements from both instruments at the two different operating modes *B* and *C*, in order to evaluate in each case the phase difference, if any, between solar p-modes. Unfortunately since Mark–I is a ground-based instrument, only a maximum of 10 to 12 hours of data per day are available in the case of perfect weather. In fact, while Golf *Mode B* operations (February-March 1996) were performed, Mark–I had a poor coverage and it was not possible to get a time series for that period with the required quality. But summer 1997 was exceptional at the Observatorio del Teide and 70 consecutive days with good daily data coverage were available; the duty cycle for the series June 26 to September 3 is as high as 40%. Concerning these data reduction and calibration to obtain the residual velocity, the technique used was the same as for the *Mode B* Golf data: calculate the ratios, at a cadence of 40 s, linearize them and subtract the known line of sight velocity components (Pallé et al. 1993). Therefore the calibrated magnitude that will be used is:

$$\mathrm{R}_{MKI} = h(v)\,\frac{I_b - I_r}{I_b + I_r} - V_{\ell s} \tag{5}$$

from which the residual time series will be formed.

2.3. SOI/MDI data

This instrument on board SOHO is one of the three helioseismic experiments (together with GOLF and VIRGO). It consists of a modified Fourier tachometer that images the Sun on a 1024^2 CCD camera and it measures the velocity and intensity continuum at the Ni 6 768 Å solar absorption line with a 60 s cadence and with a resolution of 4 arcsec (see Scherrer et al. 1995 for further details). In order to make further comparisons with solar disk integrated instruments (GOLF and Mark–I), the SOI Project provided us with a time series of integrated solar velocity signal over the solar disk (R_{SOI}) produced from the LOI-proxy signal (Toutain et al. 1997) and prepared as described by (García R.A. 1997) following the same strategy as for the previous data sets.

2.4. Data selection and timing

The different temporal coverage of the above instruments and their different data quality impose restrictions on the data selection when a comparison has to be performed. In Table 1 a summary of the data used for each instrument and their characteristics are shown. Each of the five group comparisons shown in this table has a different objective. In #1, the temporal series formed with the wing signals X_b and X_r independently calibrated, are considered. The corresponding p-modes measured from the respective power spectra should have a phase difference of 180° if they correspond to a pure Doppler shift. If the magnitudes X_i are also affected by other fluctuations (intensity, line profile changes, etc.) the phase difference will depart from 180° by an amount related with the degree of contamination. In the extreme case of reflecting pure intensity fluctuations, the resulting phase difference would be zero: that is, the fluctuations will be in phase. In #2, the above power spectra corresponding to the wing signals independently compared with the standard calibrated ratio R_{GOLF}, which is thought to be a pure Doppler shift (velocity) measurement. From the comparison #3, what will be tested is the effect on p-modes phase determinations, of the calibration procedure. The two methods are two different approaches to the same objective – namely the conversion of the intensity fluctuations into a velocity most closely approximating the Doppler shift velocity which would be derived were a full line profile available from the data. From Eqs. (2) and (4) the differences are clear; in fact while $f_b(v)$ is a function empirically deduced, $g^{\pm}(v)$ results from a line profile modeling. Comparisons,#4 and #5, have a common purpose: to compare blue wing GOLF data with simultaneous data taken with different instruments. In #4, comparison is made with a ground-based spectrometer; for this reason space data from GOLF have been windowed to exactly match the observing window of the ground instrument. In #5, aside of comparing with a different instrument's data, one additional test could be performed: by selecting two different epochs of time, precisely at maximum (+1.095 Km/s) and minimum (+0.077 km/s) values of $V_{\ell s}$, the GOLF blue component is measuring at different heights on the solar atmosphere, thus sensitivity to this effect can also be checked. In addition, the last two comparisons also allow to see any effect related with the spectral line used.

Concerning the timing for each instrument, one can see in Table 1 that the cadence of the data available is in some cases different. While this difference is not ideal, it does not in principle restrict the comparison of phases for individual p-modes. What is really crucial is the absolute time of each measurement: at 5 minute periods, 1 second error in the timing yields 1.2 °

Table 1. Characteristics of the different data sets used for the comparisons and their identification label (#1 to #5). The meaning and definition of the various magnitudes can be found in the text. In #4, the label W in GOLF *Mode C* means that the data have been windowed as the Mark–I series.

#*Id.*	*Instrument*	*Magnitudes*	Δt (s)	Period	N. Days	Comparison
#1	GOLF *Mode B*	X_b,X_r	20	19/02/96 →19/03/96	30	$X_b - X_r$
#2	GOLF *Mode B*	R_{GOLF},X_b,X_r	20	19/02/96 → 19/03/96	30	$X_b - R_{GOLF}$ $X_r - R_{GOLF}$
#3	GOLF *Mode C*	X_b	40	26/06/97 → 03/09/97	70	$X_b - \Delta S$
	GOLF *Mode C*	ΔS	80	26/06/97 → 30/08/97	66	
#4	GOLF *Mode C* ^{W}	X_b	40	26/06/97 → 03/09/97	70	$X_b - R_{MKI}$
	Mark–I	R_{MKI}	40			
#5	GOLF *Mode C*	X_b	20	20/08/96 → 17/11/96	90	$X_b - R_{SOI}$
	$\int_\odot SOI$	R_{SOI}	60			
	GOLF *Mode C*	X_b	20	20/02/97 → 20/05/97	90	$X_b - R_{SOI}$
	$\int_\odot SOI$	R_{SOI}	60			

change in the phase. Therefore, this problem has been carefully considered so that appropriate offsets have been applied to the absolute timing zero points and appropriate delays have been added to account for the varying Earth-SOHO distance to yield a consistent temporal basis for all instruments. Subsequently all of the times were converted to UT as defined on Earth. Once the time is correct, the temporal series were formed, each one with the time span shown in Table 1, with a unique time reference for each of the pairs to be compared: 0 hours U.T. of the first day of data. As an example of the residuals used, a four hour interval for each one of the different pairs of data sets described in Table 1 is shown in Fig. 2.

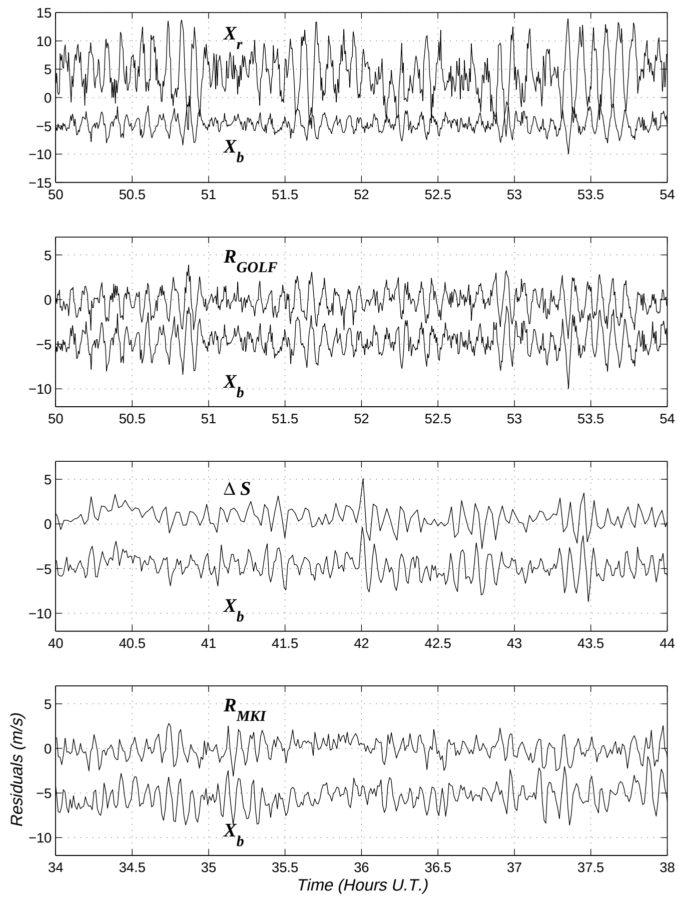


Fig. 2. Samples of four hours length corresponding to the different data sets used in the comparisons #1 to #5 (see Table 1 for their meaning). In each sub-plot, the signal X_b has been shifted by -5 m/s in order to clearly distinguish the different signals.

3. Power spectra and analysis

Following the preparation of the time series, the next step is to compute their power spectra in the 5 min region so that we can estimate the frequencies of the p-modes and our primary objective - their temporal phases. We have carried out this process using an iterative sine wave fitting (*ISWF*) method following (Pallé 1986) rather than a standard FFT. The main attraction of this method is that its ability to extract the power and phase at any frequency together with their associated statistical errors. Because this method provides only one sine wave near the target frequency it concentrates the information available for that frequency and provides a determination of the phase with less uncertainty than is available from the fft. Therefore the power spectrum for all series were calculated between 2 and 4 mHz with a frequency step of 0.1 μHz for the 30 day series (1/T = 0.386 μHz), 0.05 μHz for the 70 day series (1/T = 0.165 μHz) and 0.03 μHz for the 90 day series (1/T = 0.129 μHz). In each case, the amplitude squared and temporal phases (together with their associated errors) are considered for further analysis.

Once the spectra were obtained, the mode identification was undertaken working simultaneously on the pairs of spectra corresponding to the series described in Table 1. When the same frequency is identified in both spectra the phase difference and its propagated error is determined. In the present work, the criteria followed in the identification is simply to choose the highest peak in the vicinity of the expected mode frequency, taken from Lazrek et al. (1997). Although the mode frequency identification has no importance in this work due to the low frequency resolution available, what it is really significant is the phase difference evaluated at the same frequency bin.

An alternative way to calculate the phase difference is by means of a spectral bivariate analysis. Briefly, given two time series we compute the sine and cosine amplitudes of their Fourier spectra and from them the power spectral densities, the co-spectral density, the quadrature spectral density and the complex cross-spectral density (Koopmans 1974). After smoothing the parameters by performing a 3.8 μHz moving mean, the coherence and phase difference can be obtained. This powerful method has been previously used by Fröhlich and van der Raay (1984) and Schrijver et al. (1991). It produces very consistent results in complete agreement with the method described above (see Fig. 3).

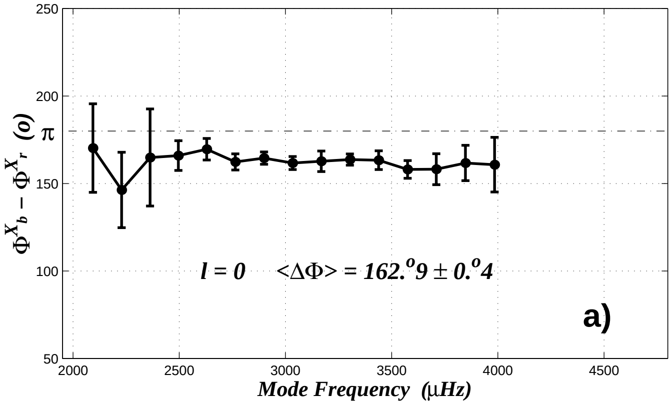
4. Results and discussion

4.1. Comparison #1

This is the most important comparison as it provides a unique way to determine whether a pure Doppler shift is being measured. As can be seen in Fig. 3a the phase difference of the ℓ=0 modes as measured by means of the independent magnitudes X_b and X_r is not 180°. In fact when the averaged phase difference is calculated, a value of 162.°9 $\pm$ 0.°4 is obtained, which is 17° which differs from what is expected for a pure velocity shift. To give more consistency to this result, a bivariate spectral analysis has been applied to the same series and a new set (see Fig. 3b) of individual phase differences was obtained. Although completely different analysis techniques have been used, it can be seen that the results are identical to one σ level. Additionally, preliminary work (Régulo et al. 1998) with similar data sets but using filtered intensities $\langle I_b \rangle$ and $\langle I_r \rangle$ rather than the calibrated magnitudes X_b and X_r, gave a mean phase difference of 161.°6 $\pm$ 1.°7, which also agrees with what we have found. In summary, the magnitudes X_b and X_r do not represent pure Doppler shifts (velocity) of the solar absorption line.

4.2. Comparison #2

In this comparison the individual wing power spectra are compared with the one obtained by using the classical calibrated ratio R_{GOLF}. By looking at its mathematical expression, see Eq. (1), it can be anticipated that since the phase difference between both wings is not exactly 180°, by subtracting the signals (numerator of R_{GOLF}) complete cancelation will not take place. The obtained results are shown in Fig. 4a together with the mean values for each one of the comparisons, where 180°have been added to the $\Delta\Phi(X_r - R_{GOLF})$ values to compress the results allowing higher resolution in the plot. Notice that the difference between the two values, that is $\Delta\Phi(X_b - R_{GOLF}) - \Delta\Phi(X_r - R_{GOLF}) = \Delta\Phi(X_b - X_r)$, is



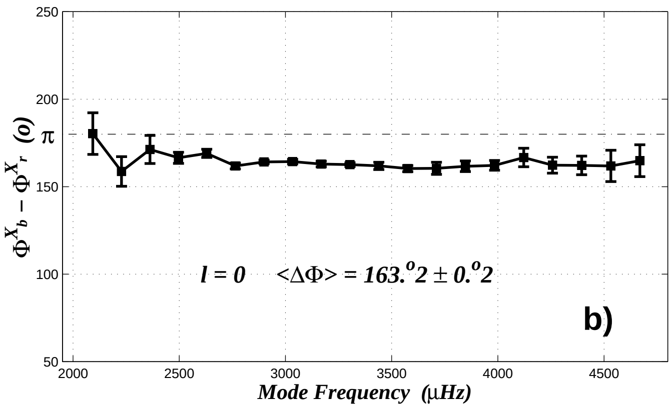


Fig. 3a and b. Phase difference between the ℓ=0 p-modes measured through the GOLF blue (X_b) and red wing (X_r) signals, on simultaneous time series. In **a** the results obtained by direct comparison of the peaks' phase while in **b** results obtained from the bivariate analysis on the same series. In both cases, $< \Delta\Phi >$ is the weighted mean of the individual values for each mode.

163° which coincides with the result obtained in the previous comparison (see Fig. 3). Therefore the standard ratio, R_{GOLF}, although thought to be representative of a pure wavelength shift, in fact has some degree of contamination which results from an averaged value of the whole effect present in the wings.

4.3. Comparison #3

This comparison was undertaken in order to see any possible dependence between signals and calibration techniques used. Again, the same time series of the blue wing signal but differently calibrated were taken, their power spectra computed and the ℓ=0 p-mode phases determined. The differences are plotted in Fig. 4b and as it can be seen it is identical to zero. Therefore this result can be interpreted in the sense that both signals X_b and ΔS are of the same nature.

4.4. Comparison #4

This comparison between GOLF and Mark–I data is important in three aspects. First, because it is between two different in-

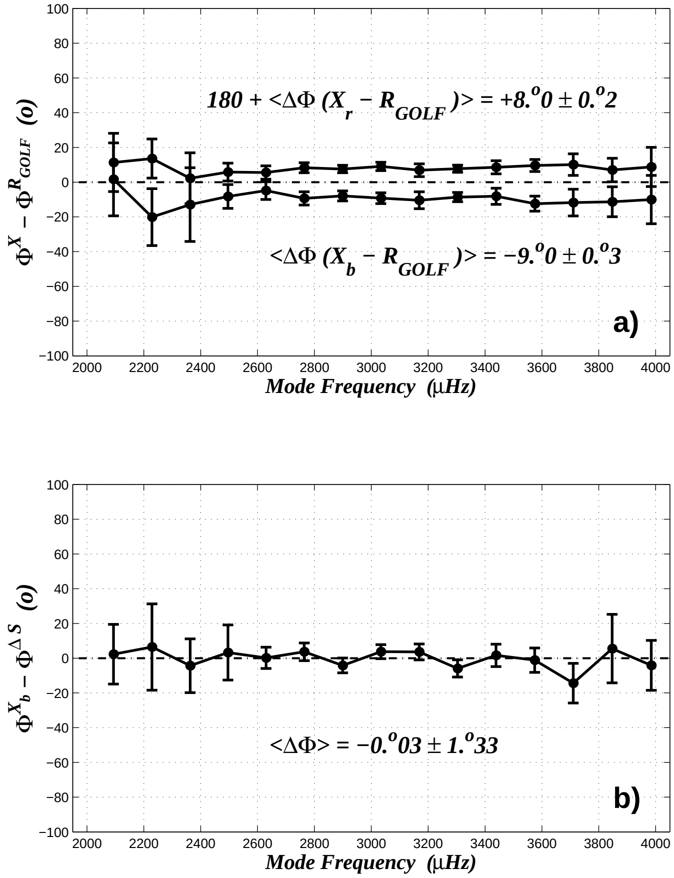


Fig. 4a and b. In **a** results obtained for the phase difference between ℓ=0 p-modes when comparing the X_b and the X_r spectra with the R_{GOLF} one; $<\Delta\Phi>$ is the resulting weighted mean value. Notice that the difference between both mean values, that is $\Delta\Phi(\mathrm{X}_b-\mathrm{X}_r)$, is 163°, which coincides with the previously obtained value (Fig. 3a). The dependence of the calibration method of the wing signal is illustrated in **b**, where the phase difference between ℓ=0 p-modes as obtained from the differently calibrated magnitudes X_b and ΔS is plotted.

struments in space and on ground. Second, because the Mark–I signal is a well known earth-based reference. Third, because it is a measurement performed in a different spectral line and therefore another height (deeper) in the solar atmosphere. These reasons support the position that Mark–I probably provides the best parameter available to compare with the GOLF X_b signal and argue about its nature. The result of the phase difference between ℓ=0 p-modes identified in both data sets is shown in Fig. 5a, where a mean value of -9.°1 $\pm$ 2.°3 is obtained. Notice that the error bars associated to each mode are bigger than in the comparison #2; this is because the duty cycle of the GOLF data has been reduced to match the one of Mark–I instrument. It is also remarkable that the mean value found fully agrees, within one σ, with the mean value found for $\Delta\Phi(\mathrm{X}_b-\mathrm{R}_{GOLF})$ in #2. Thus the obvious conclusion is that the GOLF calibrated ratio R_{GOLF} has the same nature as the Mark–I ratio, R_{MKI}. Even more, since both ratios are of the same nature and one of them, R_{GOLF}, have been shown not to be a pure Doppler shift measurement, it follows that R_{MKI} is not either.

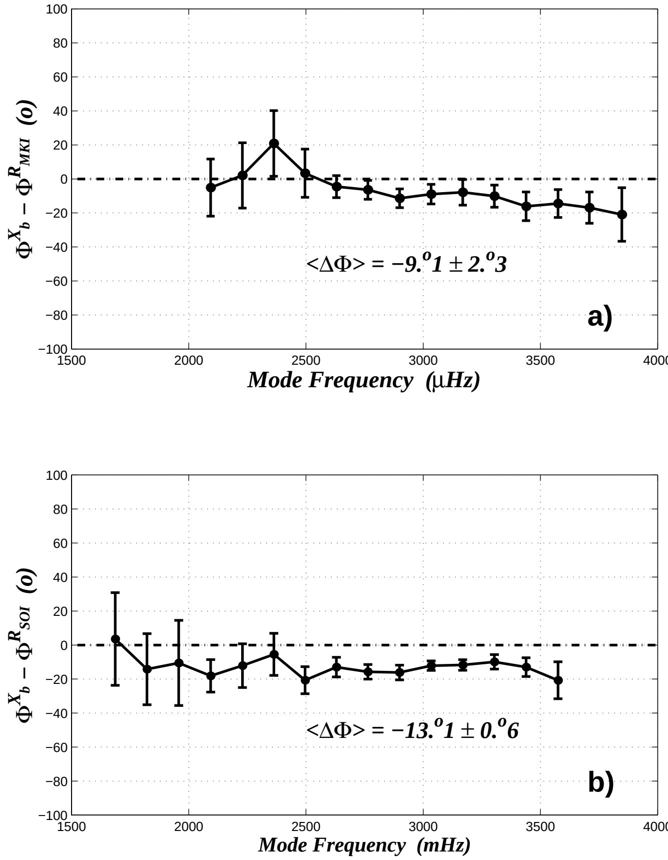


Fig. 5a and b. Differences obtained for the ℓ=0 p-modes phases using GOLF data and simultaneous data obtained with other instruments. In **a** GOLF versus Mark–I ground based spectrometer. In **b** GOLF versus SOI instrument on board SOHO. The different range of ℓ=0 modes identified in both cases is due to the different data quality and length of the series compared (see Table 1).

4.5. Comparison #5

One of the aims of this comparison is similar to the one in #4: a different instrument and a different spectral line, although in this case there is no need to window the GOLF signal. When the comparison is performed with the GOLF X_b signal (see Fig. 5b) similar, but not equal, result as in the previous case is found: -13.°1 $\pm$ 0.°6. The origin of this difference obtained with the integrated SOI velocity is not yet clear to us, although it might be due to the actual definition of SOI velocity parameter or the building of the actual series; however, given that in comparison #4 data taken at two different, but close, spectral lines have been used, there is every reason to expect that this case should yield similar results. Nonetheless, it is important to verify the expected similarity with the previous comparison.

The other aim of this comparison was to examine whether the change of the operating point on the blue wing on the solar sodium doublet, due to the seasonal change of the relative velocity Sun–SOHO, could influence the phase differences obtained between p-modes. To do that two series of SOI and GOLF were formed at precisely the time for maximum and minimum orbital velocity. When the phase differences are calculated for

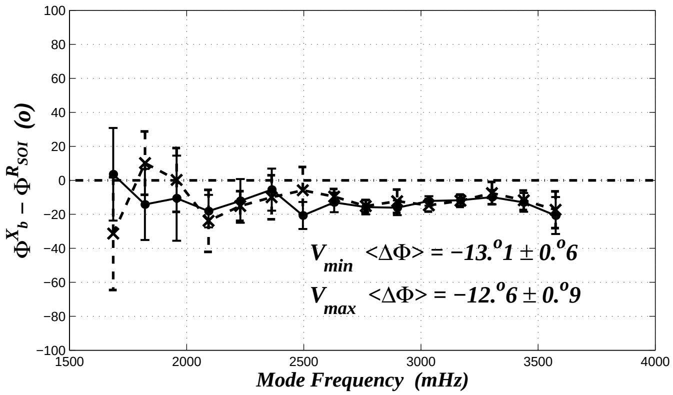


Fig. 6. Phase difference between low degree p-modes simultaneously measured in GOLF and in the SOI (integrated over the solar disk) instruments at two different epochs. The solid circle correspond to the results for the epoch of maximum line-of-sight velocity (deeper in the solar atmosphere) and the cross for the epoch of minimum (higher in the solar atmosphere)

both time series, the results shown in Fig. 6 are obtained. Within one σ level the results do fully agree.

Finally, all the results obtained above, do not depend of the selected degree ℓ of the considered p-modes: a similar behavior is obtained for low degree $\ell \leq 3$ and that is why only the $\ell = 0$ have been presented in the figures. However, the absolute phase difference between a given pair of modes, does clearly depend on their degree. Indeed, when comparing ground (Mark–I) signal with the GOLF one (X_b) the phase differences obtained are: - $9.^\circ1 \pm 2.^\circ3$ for ℓ=0, -$8.^\circ5 \pm 2.^\circ0$ for ℓ=1 and -$4.^\circ2 \pm 2.^\circ7$ for ℓ=2. Using the bivariate spectral analysis, Jiménez et al. (1998) extensively describe this results among others.

5. Conclusions

Based on the analysis described above it is concluded that:

– The phase difference of the low degree solar p-modes, as measured by the GOLF instrument in *Mode B* (simultaneous measurements X_b and X_r) is $162.^\circ9 \pm 0.^\circ4$, thus implying that such signals are not pure Doppler (velocity) shifts. This result is independent of the spectral analysis technique used to determine the temporal phases.

– The differences of individual wing p-mode phases relative to the one for the standard ratio R_{GOLF} are of around -9° , very far from $\sim$ -130° which would correspond to a phase difference between intensity and velocity measurements (Schrijver et al. 1991). Therefore, although the GOLF wing signal does not correspond to a pure wavelength shift, it is very close to it. Its degree of contamination is very low. In fact, from a simple model with two sine waves representing a pure intensity and a pure velocity fluctuation, the values for the phase difference found can be obtained by assuming that the amplitude of the intensity fluctuation is about 14% of the velocity one.

– In the present GOLF operation mode only the blue wing signal exists allowing the definition of the X_b and $\Delta\mathrm{S}$ signals, each independently calibrated. However, modes measured in both signals are strictly in phase ($-0.^\circ03 \pm 1.^\circ33$) thus showing identical nature. When the X_b signal is compared with the one obtained from a well known ground instrument, Mark–I, an identical behavior is obtained as in the case of GOLF ratio while in *Mode B*, with a phase difference of $\Delta\Phi(\mathrm{X}_b - \mathrm{R}_{MKI}) = -9.^\circ1 \pm 2.^\circ3$ for the ℓ=0 p-modes. Therefore it is concluded that the ratio measurements R_{MKI} and R_{GOLF} are also of the same nature. A similar result ($-13.^\circ1 \pm 0.^\circ6$) is obtained when comparing the X_b signal with the SOI integrated ratio R_{SOI}. The 4° difference, if significant, remains to be explained.

– Moreover, the observed differences between X_b and others, do not show any dependence on the spectral line used (Na or K) and maybe slightly with the Ni one, nor on the different position of the GOLF operating point on the solar line profile (nor on time). Furthermore the observed behavior of the phase differences are independent of the degree of the solar p-modes chosen ($0 \leq \ell \leq 3$), although the absolute values of the differences do (see Jiménez et al. 1998).

From all above results we conclude that it seems to be a general contamination on the examined velocity measurements (GOLF, SOI, Mark–I and by extension IRIS and BiSON instruments) concerning the p-mode solar oscillations, so that what is measured is not a pure wavelength shift. This effect is neither attached to a particular instrument, nor to an specific solar spectral line or to a particular analysis technique. As a tentative explanation it can be thought as something related to the physics and thermodynamics of the oscillation itself (temperature and opacity variations), although more work and data are required to go further in quantifying this effect.

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