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Low frequency signal in the GOLF measurements

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Abstract. This paper shows the results obtained using a revisited method to normalize the velocity evaluation extracted from the measurements, for roughly 14 years of GOLF data. For the search of g modes, we calculate the low frequency power spectrum of the signal with 2 different approaches:

- The classical calculation of the power spectrum of the velocity signal.
- An alternative calculation, extracting first the variations along the time of the p-mode frequencies, then calculating the power spectrum of those frequency modulation [4].

Both spectra are compared to the g-mode frequency spectrum calculated for a solar model. Several observed frequencies are in close agreement with the calculated g modes. A careful statistical analysis of this result should now follow.

1. Introduction

The solar observatory SoHO carries several instruments designed for helioseismology. Now a long period has been devoted, in space as at ground, to detect solar g modes. The results remain today controversial, even the detectability of such oscillations is not proved [1]. Nevertheless, the low frequency part of the solar spectrum is very rich in sharp lines and some of them seem to be related to very stable features, not to noise fringes due to the solar convection noise. In addition this convection noise produces a low frequency increase of the energy. On other hand, the knowledge of the p-mode spectrum and of the solar model allow to calculate the probable spectrum of the g modes of the rotating Sun. This paper shows how the observations and the calculations can fit together. A second part is a study of the p-mode frequency variations, with the assumption of a cross modulation allowing to detect g modes.

2. The power spectrum analysis

The new procedure used here for the velocity calibration [2] produces an almost constant amplitude signal envelope over the whole duration of the observations (Fig.1). Compared to our former procedure, the conversion factor of the signal to the surface solar velocity is more effectively corrected from the variations related to the orbital parameters: the non linearity related to the orbital velocity, the temperature shift of the instrument related to the solar distance, a faint non-thermal drift with the time. The power spectrum of this velocity is then calculated with the 2.5 nHz frequency resolution corresponding to the total duration of GOLF observations. The low-frequency part of this spectrum is shown Fig.2.

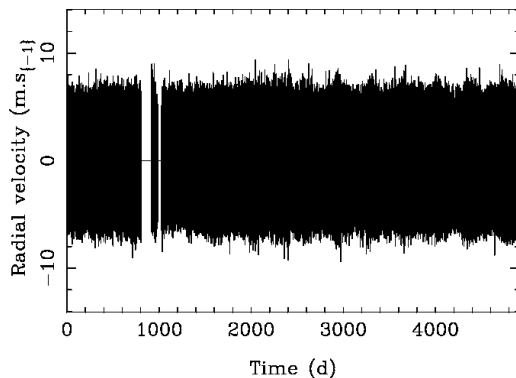


Figure 1. 14 years of velocity signal from GOLF, starting Apr. 10, 1995).

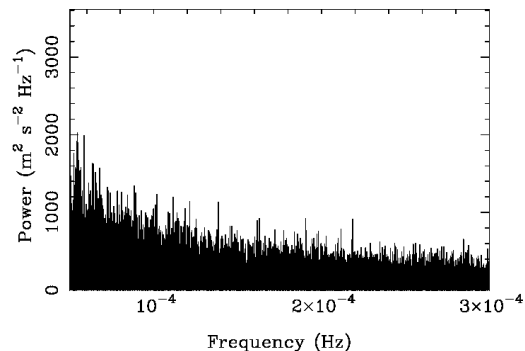


Figure 2. The velocity power spectrum in the frequency domain searched for g modes.

2.1. The lines in the 217 μHz to 221 μHz domain

In the low frequency range of the power spectrum, the new procedure used may result in a different detection of a peculiar spectral line. Obviously the power spectrum of a time sequence depends on the variation of the weighting of the signal related to a variable sensitivity along the time.

Fig. 3 shows the spectral density from 217 μHz to 222 μHz : The frequency value measured for the highest line is 218.585 μHz , the line at 220.7 μHz previously identified [5] is buried in the surrounding noise in the spectrum calculated here for 14 y of GOLF observations. A close line at 218.314 μHz is found in [3].

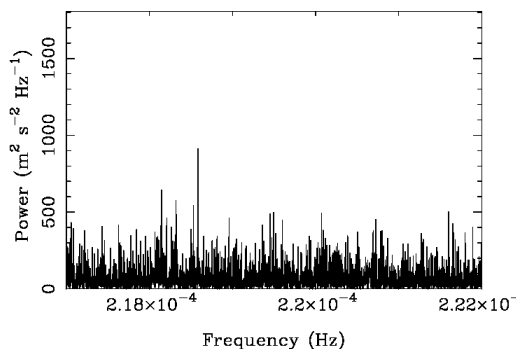


Figure 3. Part of the power spectrum: the 217 μHz to 222 μHz interval.

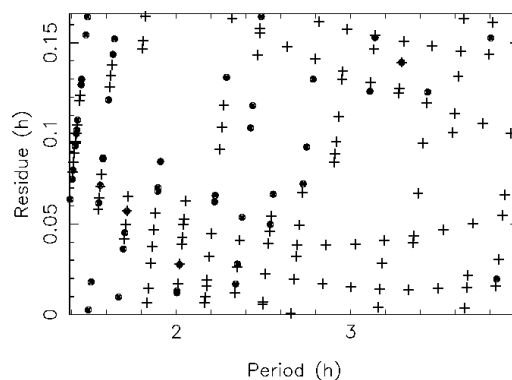


Figure 4. The periods detected in the velocity power spectrum (●) and calculated for the observable g modes for $l \leq 3$ (+).

2.2. Search for a calculated g-mode pattern

The solar model is calculated using the CESAM code [6] and calibrated in age and luminosity. The rotation, as deduced from the inversion of helioseismic data, varies with depth and latitude in the convective zone. The rotation frequency is constant $\Omega = 433$ nHz for the radiative zone and the solar core [7]. The calculations are made into inertial coordinates and translated into synodical values.

In order to make a simple detection of the higher peaks in the power spectrum, the well-known increasing trend in the low-frequency domain is cleared thanks to a normalization by a running mean filtering - assuming the common increase of signal and background is due to an increasing energy source. This results in sharp lines in a flat noisy background. The observed power spectrum is then reduced to the small number of lines having the highest amplitude in the considered frequency domain. All detected lines are sharp lines, either long phase-coherent oscillation or noise.

The comparison of the frequencies detected with the calculated g-mode spectrum has to be done globally for all g-mode in the band pass available for the observations and with a very high spectral resolution. We use a *spectre echelle* calculated for the periods (Fig.4). Unlike the p modes, the spacing of successive modes depends on the degree l . For a given period P we calculate the residual number $R = P - kP_l$ where $kP_l < P < (k+1)P_l$ and the folding factor P_l reflects the periodical behaviour of the asymptotic series of g modes. For a given degree l , $P_l = P_0 / \sqrt{l(l+1)}$ where the characteristic period P_0 depends of an integral function over the solar interior of the buoyancy force. In addition, a given mode is separated into several components by the solar rotation depending on the tesseral order m . This almost constant splitting in a frequency scale results in an increasing spacing of components as the period increases. We select the periods of geometrically visible modes ($l+m$ even) for which the geometrical averaging over the solar disk is minimum. Fig.4 shows the periods calculated for the degrees $l = 1, l = 2, l = 3$, a mode is shown as a point at coordinates (P,R), we use a folding factor P_1 adjusted to display as clearly as possible the series of points for $l = 1$.

If the actual value of P_l determines the pattern associated to the periods for a given value of the degree l , it does not change the relative display of 2 close periods. The same diagram can display the calculated series for different l , together with the periods detected in the observations. On this display, the coincidence of the model with the observations are clearly visible. Roughly 50% of the highest lines in local domain of the power spectrum shown Fig.4 coincide with a calculated mode or are very close to it.

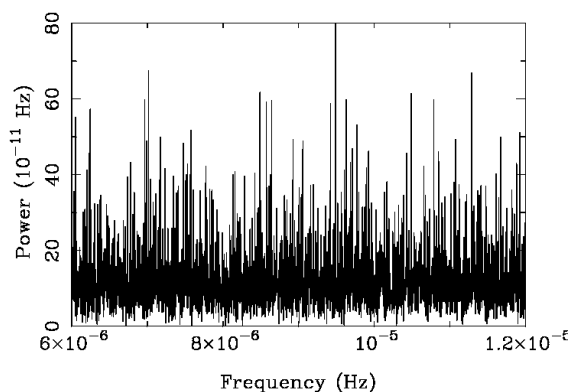


Figure 5. Averaged cross spectrum of the p-mode frequency variations measured for the 14 y of observation.

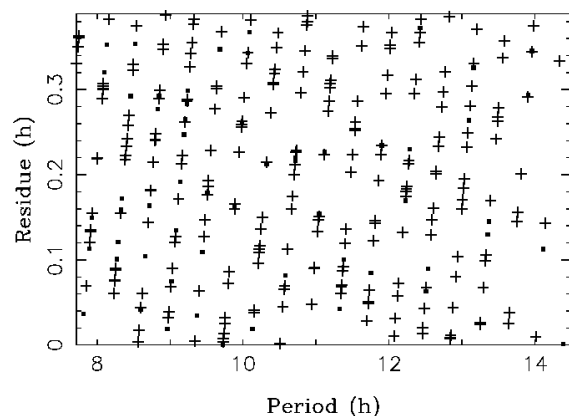


Figure 6. Diagram of periods detected in the p-mode frequency modulation (●) and of the periods calculated for splitted g modes of degree $l = 1, 2, 3$ (+).

3. Power spectrum of the p-mode frequency variations

A p-mode frequency is related of the physical condition of the corresponding resonant cavity. This frequency is related on the sound speed which depends on temperature and then them

perturbations, as g-mode oscillations may induce. The idea is then to study the frequency modulation of the acoustic modes and compare the lines detected in the power spectrum to a theoretical spectrum of g modes. We use the method described in the previous paper [4] with a new set of numerical parameters, in order to improve precision and spectral resolution.

The frequency of the p modes for degree $l = 1$ and radial order $n = 11$ to $n = 25$ is measured on short time intervals, using a correlation of the power spectrum with an averaged power spectrum used as constant reference. The limits of n is fixed by the amplitude of mode, the width of the spectral lines and their dependency on the solar activity. In order to obtain a mean noiseless spectrum, we calculate the averaged cross-spectrum of the time functions giving the frequency of each mode.

Due to intrinsic limitations of the observed band pass, the analysis address the asymptotic domain of the g-mode spectrum. The comparison with the observations is made as in Sec.2.2. Presently, the longest observed periods (above 14 h) have no calculated counterpart, due to the resolution of the radial grid of the solar model. A preliminary question arises: which g modes are observable? Let assume as a first approach that the geometry of the observable g modes ($l + m$ even) is independent on the physical observable (luminosity, radial velocity, p-mode frequency variations). Again, the display is optimized for a given value of l , for which the asymptotic series are visible (Fig.6). The periods are displayed for modes of degree $l = 1$ to $l = 3$ up to the longest calculated values. The rotational splitting produces here a complex pattern. Close coincidences of the model with the observations are detected. A statistical study should follow in order to evaluate the probability of a real g-mode detection.

4. Conclusion

On the long term observations analysed here, the previously-called 220.7 μHz line, mainly visible in the intensity variations [5], is not detected in the velocity spectrum.

Even if a small number of detected lines corresponds to calculated modes, it may confirm the validity of the numerical model, including the rigid rotation below the convective zone.

Several detected lines in the power spectrum of the velocity calculated with the new calibration process are in good agreement with the model, mainly for $l = 3$. The statistical significance of this detection remains to be estimated.

The power spectrum of the frequency modulation of the p modes contains several long period g-mode of the calculated series, either for degree $l = 1$, $l = 2$, $l = 3$. Again the statistical significance must be estimated.

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