# TRI-PHONIC HELIOSEISMOLOGY: COMPARISON OF SOLAR P MODES OBSERVED BY THE HELIOSEISMOLOGY INSTRUMENTS ABOARD SOHO


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**Abstract.** The three helioseismology instruments aboard SOHO observe solar p modes in velocity (GOLF and MDI) and in intensity (VIRGO and MDI). Individual time series of 2 months are compared and confirm that the instruments indeed observe the same Sun to a high degree of precision. Power spectra of 108 days are compared showing systematic differences between mode frequencies measured in intensity and in velocity. Data coverage exceeds 97% for all the instruments during this interval. The weighted mean differences (V-I) are -0.1 $\mu$Hz for $l$=0, and -0.16 $\mu$Hz for $l$=1. The source of this systematic difference may be due to an asymmetry effect that is stronger for modes seen in intensity. Wavelet analysis is also used to compare the shape of the forcing function(s). In these data sets nearly all of the variations in mode amplitude are of solar origin. Some implications for structure inversions are discussed.



**Key words:** Helioseismology – SOHO Mission


## 1. Introduction

On board the SOHO spacecraft are 3 helioseismology instruments: GOLF (Global Oscillations at Low Frequency), VIRGO (Variability of solar IRradiance and Gravity Oscillations) and MDI (the Solar Oscillations Investigation's Michelson Doppler Imager). MDI observes the Sun in velocity and intensity using a detector with 1024×1024 pixels. Unresolved observations of the Sun-as-a-star are made in velocity by GOLF and in three different wavelengths bands in brightness and in total irradiance by VIRGO. In addition, VIRGO's LOI instrument images the Sun near 500 nm onto 12 pixels. All three instruments are described in detail in the special issue of Solar Physics on SOHO, vol 162, 1995 (Scherrer *et al.*, Gabriel *et al.*, and Fröhlich *et al.*).

In this paper we report on the first comparison of the time series and mode spectra measured by these instruments. The directly compared time series begin 24 May 1996 and end 23 July 1996. The spectra are computed from a longer time series of 108 days that ends 8 September 1996. Finalization of the low-$l$ intensity component of the MDI structure program determined the start date of the time series. The ending date for the power spectra was dictated by a temporary interruption of VIRGO data acquisition on 9 September 1996, probably caused by high energy particle irradiation. In the next section we describe how the various data sets were obtained. In the two following sections, we compare the time series, the spectra, and the p mode frequencies derived from the 108-day power spectra; time-frequency analysis is also used for comparison.

## 2. The Data Sets

### 2.1 GOLF VELOCITY

The performance of the GOLF instrument has been reported by Gabriel *et al.*(1997), and the p-mode analysis by Roca-Cortés *et al.*,(1997). GOLF measures full disk integrated solar velocity using a sodium resonance cell (Approximate Observation Height above $\tau_{500} = 1$ (AOH): 500 kms) to detect intensity at wavelengths near the D1 and D2 spectral lines. Since 11 April 1996 the instrument has been able to measure the intensity in only the blue wing of the sodium lines. This means that the 'velocity' signal obtained by GOLF is actually a combination of the true velocity signal, caused by displacement perturbations, and an intensity signal, caused by temperature and opacity variations. Phase analysis of both signals (when this was possible, prior to April 1996) shows that the actual signal is mostly due to a Doppler shift; the remaining pure 'intensity' perturbation is minute, being responsible for a phase shift of only a few percent (Régulo *et al.*, 1996). Therefore the observed signal has been calibrated into velocity with an absolute precision of about 20%. This has to be taken into account when one wants to measure the phase shift between the GOLF 'velocity' signal and the VIRGO or MDI 'intensity' signals. The basic sampling rate of the instrument is 5 seconds with a duty cycle of 80%. For this study the data have been averaged into 60 second bins. The data coverage for the 108-day time series was better than 99.99%.

### 2.2 VIRGO Intensities

The overall performance of the VIRGO instrument has been reported by Fröhlich *et al.*(1997). The VIRGO instrument has several components: Sunphotometers, radiometers, and LOI. Each is described below.

#### *2.2.1 Sunphotometers (SPM)*

The VIRGO/SPM comprises 2 sunphotometers with 3 channels at 402 nm, 500 nm and 862 nm that view the Sun as a star (AOH for all three: a few tens of kms). The sampling rate of VIRGO/SPM is 60 sec with a 94% duty cycle. The VIRGO sampling is offset by 30s relative to the other two SOHO helioseismology instruments. This is because VIRGO is the only instrument synchronized to the SOHO daily pulse sent every midnight. The daily pulse was synchronized to Temps Atomique International before 27 March 1996, and thereafter to Universal Time. At that time the two standards were 30 sec apart. The data coverage for the 108-day time series is 99.17%.

#### *2.2.2 Total Irradiance*

On VIRGO there are 2 radiometers that measure the radiative output of the Sun: DIARAD and PMO6 (Fröhlich *et al.*, 1997). The DIARAD instrument has a sampling rate of 120s and is therefore not suitable for p-mode analysis. On the other hand the PMO6 is sampled every 60s with a 31% duty cycle with samples taken 20 s later than the PMO6. This modification from the original mode of operation (Fröhlich et al, 1995) is primarily due to the shutter not working as expected. Only the PMO6 is used for the p-mode comparison (AOH: close to red channel of the SPM). The data coverage for the 108-day time series is 97.08%.

#### *2.2.3 Luminosity Oscillations Imager (LOI)*

The performance of the VIRGO/LOI instrument has been reported by Appourchaux *et al.*(1997). The VIRGO/LOI images the Sun at 500 nm on a 12-pixel photodiode allowing detection of modes with $l \leq 8$ (AOH: same as green channel of the SPM). The sampling rate of VIRGO/LOI is 60 sec with a duty cycle of 99% for the scientific pixels, and 5% for the guiding pixels. The LOI is in phase with the other instruments of VIRGO. The LOI data from the 12 scientific pixels can be combined to obtain a measurement of the Sun seen (nearly) as a star. The data coverage for the 108-day time series was better than 99.9%; most of the gaps are due to spacecraft momentum managements that create brief spikes in the data string.

### 2.3 MDI Velocity and Intensity

The performance of the Michelson Doppler Imager instrument has been reported by Scherrer *et al.*, (1997). MDI measures velocity in the 6768 Ni I line using a pair of tunable Michelson interferometers with a narrow fixed passband Lyot. The velocity is computed from filtergrams taken at 4 wavelengths across the spectral line (AOH: 250-300 kms). The continuum intensity and line depth are computed from these and an additional filtergram at another wavelength.

The data used here come from a proxy that sums the million full-disk 2-arcsec pixels into 180 bins that subdivide the pixels of the VIRGO/LOI (Appourchaux *et al.*, 1997). The 12 LOI scientific pixels are divided as follows: the 4 North-South pixels are each divided into 17 bins and the 4 East-West and 4 Central pixels into 9 bins each; the 4 guiding pixels are each divided into 10 bins (see Appourchaux *et al.*, 1997 for the nomenclature of the pixels). For comparison with the full disk integrated signals of VIRGO/SPM and GOLF, we averaged the 140 non-limb LOI-proxy bins to determine a 'full disk' signal. Each LOI scientific pixel was also compared directly with its MDI counterpart, by averaging over the corresponding bins. For this analysis, the sampling rate of MDI is 60 sec in phase with GOLF, normally with a 5% duty cycle. The data coverage for the 108-day time series is 97%.

## 3. Time Series Comparison

These measurements are of interest because they serve as diagnostics of the solar interior, most directly through analysis and interpretation of the p-mode spectra. For this, comparisons of p modes measured in velocity and intensity are quite interesting. Another important use of these data is to understand the longer-term variations that are caused by incoherent solar signals (sometimes referred to as solar noise). This will be essential to the search for g modes, yet another powerful tool for sounding the deepest solar interior. To identify g modes, we must find a way to identify and then remove the comparatively large signals generated by the Sun through non-oscillatory, long time-scale processes. Only in this way will we be able to isolate the g modes. For time scales longer than about 1 hour, the frequency confusion and low amplitude expected for the g modes makes the search difficult. This is the domain where we most need to develop models of incoherent solar processes.

Each of the helioseismology instruments on SOHO measures a solar signal that samples the solar surface in a different way. Visual comparison of the time dependence shown in Fig. 1 makes it clear that these incoherent processes influence each instrument in distinctly different ways. The VIRGO instruments respond rather distinctly to the passage of sunspots, especially between days 45 and 49. Note the apparent temporal offset between GOLF and VIRGO in responding to the sunspot. This is due to the fact that the sunspot affect the velocity and intensity signals differently. Two ground-based indicators of activity are included, the Magnetic Plage Strength Index

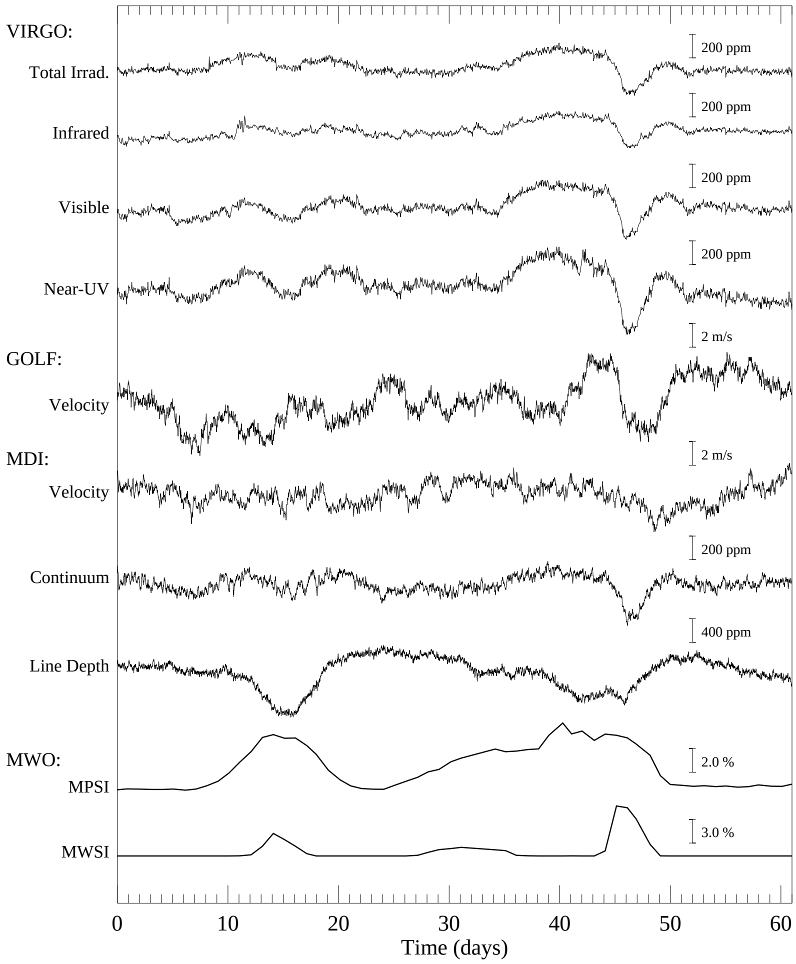


Fig. 1. Comparison of the long-time trends for various observable from VIRGO, GOLF and MDI during the period of May 24 through July 23, 1996. Reductions and calibrations of these quantities are still under study and future modifications of the results shown are possible. Each MDI signal was detrended with a 3rd order polynomial. The GOLF velocity during this period was extracted from a 283 day long data set which was detrended with an 8th order polynomial. The VIRGO data was detrended with a 5th order polynomial. Also included in the plot are the Magnetic Plage Strength Index (MPSI) and the Mount Wilson Spot Index (MWSI) which show a relative measure of plage and spot activity respectively. The percent change shown for MPSI and MWSI are relative to their typical respective values during solar maximum. All the above signals were smoothed using a 1-hour boxcar window except for the MPSI and the MWSI values which are daily averages.

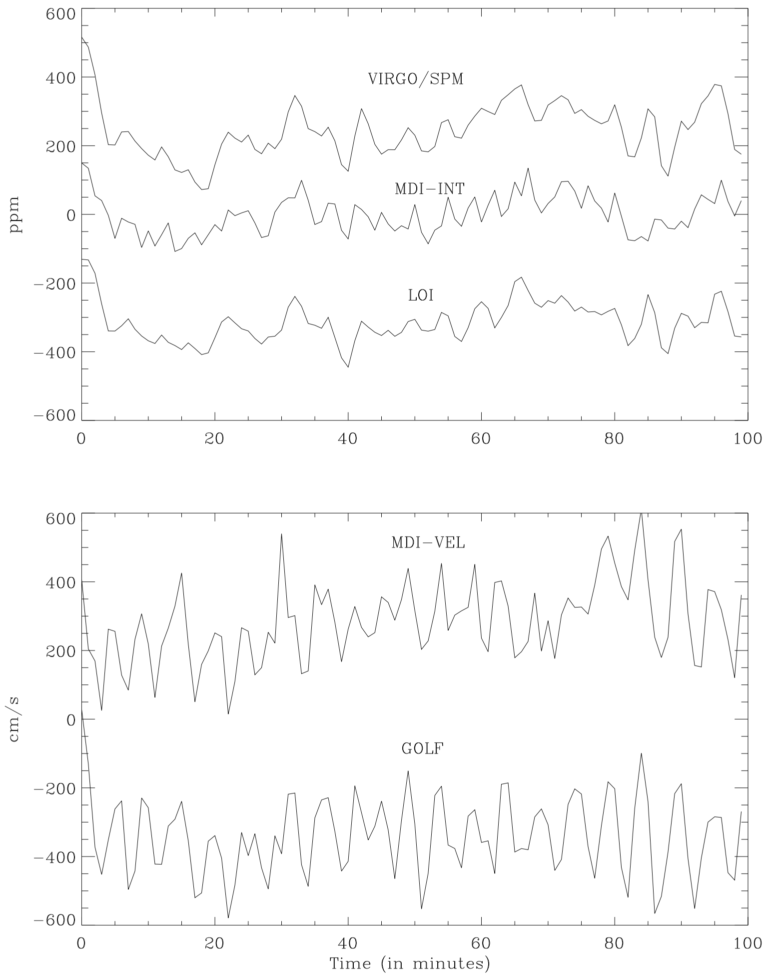


Fig. 2. (upper panel) Time series of the full disk integrated intensity of the VIRGO/SPM blue channel (top), the MDI LOI-proxy continuum (middle) and the VIRGO/LOI (bottom) for 24 May 1996 starting at 6:40 UT; the curves have been displaced by 300 ppm relative to each other. (lower panel) Comparison of the GOLF velocity time series (bottom) and the averaged MDI LOI-proxy velocity (top) for 24 May 1996.

and the Mt. Wilson Sunspot Index (Ulrich, 1991).

Figure 2 shows 100 minutes of the full-disk time series observed by several of the instruments on 24 May 1996. The agreement among the instruments in intensity and in velocity is quite stunning. It shows that all 3 instruments do observe the same Sun, and they do so to high precision. The two VIRGO instruments agree very well with each other; the MDI intensity is somewhat noisier. The intensity and velocity time series look different due to a higher

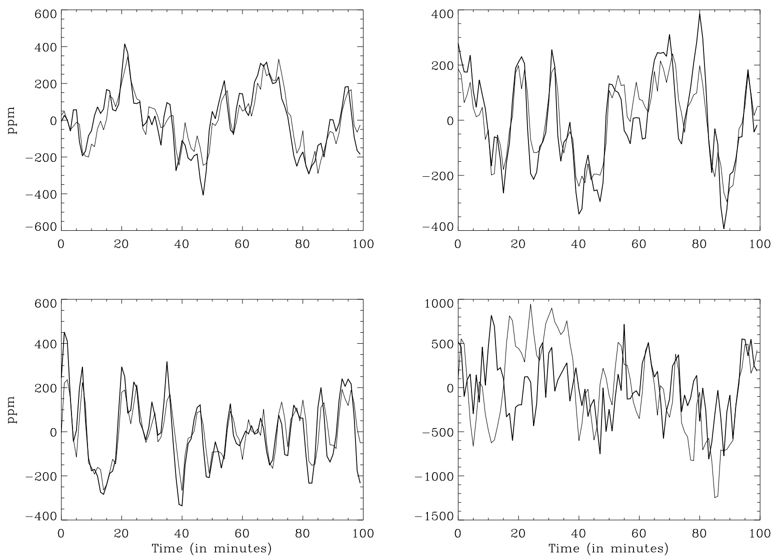


Fig. 3. Time series of individual LOI pixels (bold line) and the corresponding MDI LOI-proxy bins (thin line) for 24 May 1996 starting at 6:40 UT. Top-left: Pixel 1 (a North-South pixel); Top-right: Pixel 5 (an East-West pixel); Bottom-left: Pixel 9 (a central pixel); and Bottom-right: Pixel 13 (a guiding pixel). See Appourchaux *et al.*(1997) for the pixel numbering scheme.

sensitivity to p modes seen in velocity and to different characteristics of the low frequency noise.

Figure 3 shows the time series of selected LOI pixels and the equivalent averages of the corresponding MDI LOI-proxy continuum bins. For each of the scientific pixels the agreement is similar to Fig. 2. For the guiding pixels there is a clear discrepancy. This may be due to the fact that for the guiding pixels the LOI and MDI data are not taken simultaneously. Though the duty cycle for each is 5% at the limb, the MDI sampling takes place throughout the minute.

In Tables I and II we have summarized how similar is the Sun observed by the various SOHO instruments. The VIRGO shifts were corrected for computing the correlations. The p-mode correlations between the intensity signals is very high; the lowest correlation is obtained with PMO6 intensity signal which is also the noisier. The high temporal shift between intensity and velocity is a phase effect. For the p modes this phase shift is between -90° and -110°; it is in good agreement with the correlation found in Table I. For frequencies below 1 mHz, lower correlations are related to the solar noise and other low frequency noise. For instance the LOI has a higher noise at very low frequency than the SPM, due to daily perturbations of the shape of the solar image (Appourchaux *et al.*, 1997). It is worth pointing out that the

TABLE I

Correlation for frequencies above 1 mHz (p modes) for a 31-day time series starting 24 May 1996 at 0:00 UT.(top part) Maximum correlation, (bottom part) Shift in sec for the maximum correlation. All shifts in sec have been corrected from the various offsets in the different samples. Please note that the time shifts are given for completness; especially, they should not be used to deduce a mean phase shift between intensity and velocity.

| Ins. | LOI | Blue | Green | Red | PMO6 | $MDI_I$ | $MDI_V$ | GOLF |
|---|---|---|---|---|---|---|---|---|
| LOI | 1.000 | 0.942 | 0.939 | 0.908 | 0.589 | 0.594 | 0.389 | 0.369 |
| Blue | | 1.000 | 0.981 | 0.948 | 0.613 | 0.618 | 0.400 | 0.382 |
| Green | | | 1.000 | 0.953 | 0.613 | 0.618 | 0.400 | 0.378 |
| Red | | | | 1.000 | 0.605 | 0.610 | 0.372 | 0.344 |
| PMO6 | | | | | 1.000 | 0.390 | 0.252 | 0.239 |
| $MDI_I$ | | | | | | 1.000 | 0.246 | 0.237 |
| $MDI_V$ | | | | | | | 1.000 | 0.753 |
| GOLF | | | | | | | | 1.000 |
| LOI | 0.00 | -2.43 | -0.43 | -8.09 | -6.30 | -3.79 | +124.02 | +250.15 |
| Blue | | 0.00 | +1.19 | -6.56 | -2.59 | -3.23 | +125.71 | +251.83 |
| Green | | | 0.00 | -8.42 | -4.85 | -5.40 | +122.34 | +262.76 |
| Red | | | | 0.00 | +2.93 | +1.19 | +148.82 | +273.69 |
| PMO6 | | | | | 0.00 | -1.00 | +122.37 | +242.61 |
| $MDI_I$ | | | | | | 0.00 | +142.10 | +244.69 |
| $MDI_V$ | | | | | | | 0.00 | +36.74 |
| GOLF | | | | | | | | 0.00 |

correlations between intensity and velocity has a different signature below 1 mHz than above 1 mHz.

The remarkable agreement among the signals detected by the different instruments, both for the ‘noise’ and for the p modes, can be used to our advantage to isolate different phenomena. For instance, we could use a reference instrument to correct the low frequency noise. The goal is to reduce the solar noise and enhance the g modes. This might be less difficult if the g modes could have somewhat different signatures in the different instruments.

## 4. P-Mode Comparison

### 4.1 Frequencies

Examples of 108-day full-disk and $l = 0$ spectra are shown in Figs. 4 and 5 (resolution: 0.107167 $\mu$Hz). No oversampling or window taper was used for computing the spectra; this ensures that the frequency bins are statistically

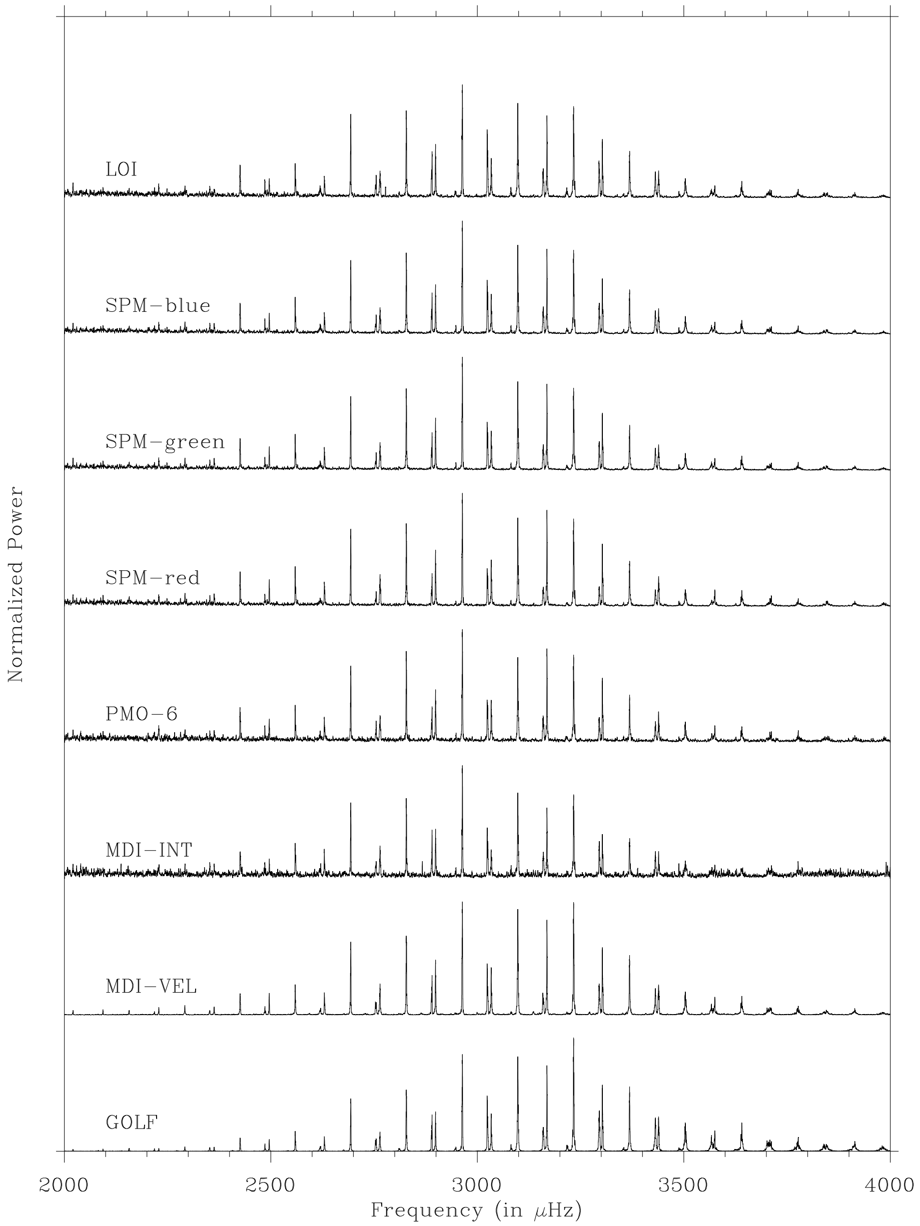


Fig. 4. Full disk power spectra derived from the time series of the various instruments. Each spectrum has been normalized to the maximum power in the frequency range and offset by an equal amount.

TABLE II

Correlation for frequencies below 1 mHz (solar noise) for a 31-day time series starting 24 May 1996 at 0:00 UT.

| Ins. | LOI | Blue | Green | Red | PMO6 | $MDI_I$ | $MDI_V$ | GOLF |
|---|---|---|---|---|---|---|---|---|
| LOI | 1.000 | 0.407 | 0.467 | 0.386 | 0.154 | 0.517 | -0.072 | 0.221 |
| Blue | | 1.000 | 0.933 | 0.760 | 0.586 | 0.407 | -0.044 | 0.239 |
| Green | | | 1.000 | 0.654 | 0.376 | 0.391 | -0.031 | 0.235 |
| Red | | | | 1.000 | 0.583 | 0.443 | -0.048 | 0.241 |
| PMO6 | | | | | 1.000 | 0.191 | -0.029 | 0.106 |
| $MDI_I$ | | | | | | 1.000 | -0.081 | 0.226 |
| $MDI_V$ | | | | | | | 1.000 | 0.505 |
| GOLF | | | | | | | | 1.000 |

independent (Gabriel, 1994). The p-mode frequencies have been measured using maximum likelihood estimators (Anderson *et al.*, 1990). The full disk integrated spectra were fit assuming equal amplitudes for all the components in a multiplet. All of the fits were performed with the same code. The 'reference' frequencies are those of the VIRGO/LOI 108-day power spectra. Figure 6 shows the frequency comparison. The $l = 0, 1$ spectra show systematic differences; the mean frequency differences are given in Table III. The systematic difference manifests itself in Fig. 5 as increased power at higher frequencies in intensity relative to velocity.

## 4.2 Time-Frequency Analysis

Another way to compare helioseismic time series is to look at the temporal behavior of the p modes, which are known to vary strongly in power (Baudin *et al.*, 1994; Leifsen *et al.*, 1995). The method used here is derived from wavelet analysis (Baudin *et al.*, 1996). It has been applied to the initial 61-day time series of the various instruments in $10\mu$Hz bands centered on the frequencies of the p modes identified above. An example is given in Fig. 7.

The observed power variations are consistent with convective excitation of p modes (Woodard, 1984); as are the apparent frequency variations (Garcia *et al.*, 1996).

In previous data sets, the non-solar noise present in the data was expected to yield spurious variations of power and/or frequency. The comparison of the data from the helioseismic experiments on board SOHO shows their excellent quality. For the modes of high amplitude (in the frequency range $2700\ \mu\text{Hz} \leq \nu \leq 3500\ \mu\text{Hz}$), the distribution of power versus time and frequency is strikingly similar for the different time series, showing that the

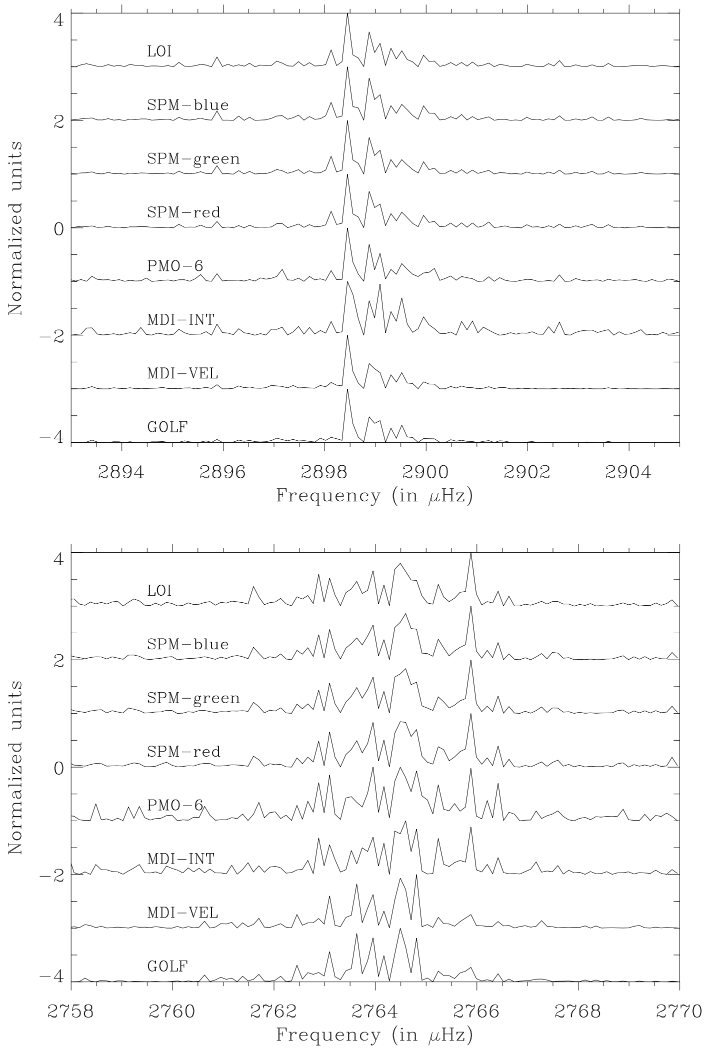


Fig. 5. Power spectra of $l = 0$ modes observed by various instruments: (top) $n = 20$, (bottom) $n = 19$. Each spectrum has been normalized to the maximum power in the frequency range and offset by an equal amount.

variations are of purely solar origin. It must be noted that this applies for *all* of the time series, including those with an intrinsically lower signal to noise ratio. The analysis of lower amplitude modes may show discrepancies between velocity and intensity, the latter being noisier. Nevertheless, the power distributions in intensity measurements from different instruments are very similar, showing clearly that the origin of this distribution is solar, not instrumental.

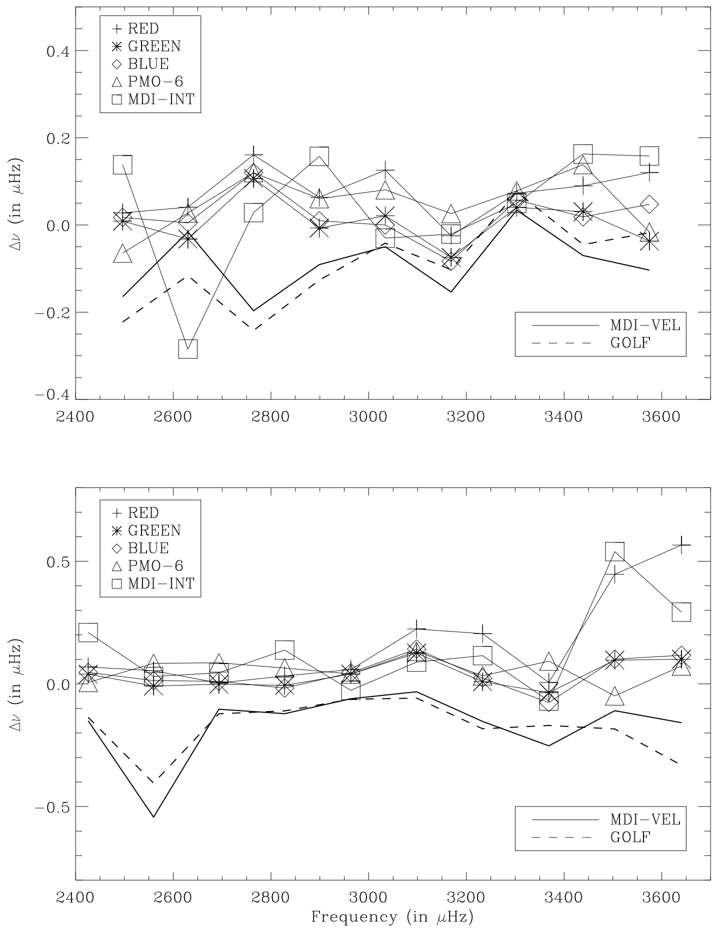


Fig. 6. The frequency differences of GOLF, the MDI LOI-proxies, and VIRGO/SPM relative to VIRGO/LOI for $l = 0$ (top panel) and $l = 1$ (bottom panel). This is for the 108-day time series. A systematic shift is clearly visible between the intensity and velocity measurements. It is premature to determine whether the systematic difference has a frequency dependence.

Figure 8 shows also how the amplitude envelopes of an $l = 0$ mode varies with time for the different instruments. The envelopes look qualitatively very similar to those measured by Toutain and Fröhlich, (1992). Table IV summarize the correlation between the envelope. The correlation between intensity and velocity is lower than for intensity/intensity or velocity/velocity.

TABLE III

Frequency differences with respect to the LOI intensity modes. This is a weighted mean over 9 modes ($17 \leq n \leq 25$) for $l$=0 and over 10 modes for $l$=1 ($16 \leq n \leq 25$). The error bars are 0.049$\mu$Hz and 0.035$\mu$Hz for $l = 0$ and $l = 1$, respectively. The error bars are derived from the LOI frequency error bars averaged optimally over the modes.

| Instrument | $l = 0$ (in $\mu$Hz) | $l = 1$ (in $\mu$Hz) |
|---|---|---|
| SPM/Blue | +0.010 | -0.001 |
| SPM/Green | +0.003 | +0.008 |
| SPM/Red | +0.058 | +0.063 |
| PMO6 | +0.044 | +0.069 |
| MDI Intensity | +0.046 | +0.032 |
| MDI Velocity | -0.094 | -0.174 |
| GOLF | -0.101 | -0.147 |

TABLE IV

Correlation for the envelopes shown in fig.8.

| Ins. | LOI | Blue | Green | Red | PMO6 | MDI$_I$ | MDI$_V$ | GOLF |
|---|---|---|---|---|---|---|---|---|
| LOI | 1.00 | 0.96 | 0.96 | 0.96 | 0.77 | 0.79 | 0.63 | 0.69 |
| Blue | | 1.00 | 0.99 | 0.97 | 0.81 | 0.81 | 0.64 | 0.70 |
| Green | | | 1.00 | 0.99 | 0.79 | 0.80 | 0.64 | 0.70 |
| Red | | | | 1.00 | 0.77 | 0.79 | 0.63 | 0.72 |
| PMO6 | | | | | 1.00 | 0.66 | 0.55 | 0.64 |
| MDI$_I$ | | | | | | 1.00 | 0.49 | 0.54 |
| MDI$_V$ | | | | | | | 1.00 | 0.93 |
| GOLF | | | | | | | | 1.00 |

## 5. Discussion

The systematic difference between the frequencies of the $l = 0, 1$ modes measured in intensity and velocity is a very significant result of this analysis. This difference is also present in the time-frequency analysis: the velocity has slightly more power at lower frequencies than the intensity. The results presented in Table III clearly show a shift between the measured frequencies of the velocity and intensity modes. There are also indications of shifts seen

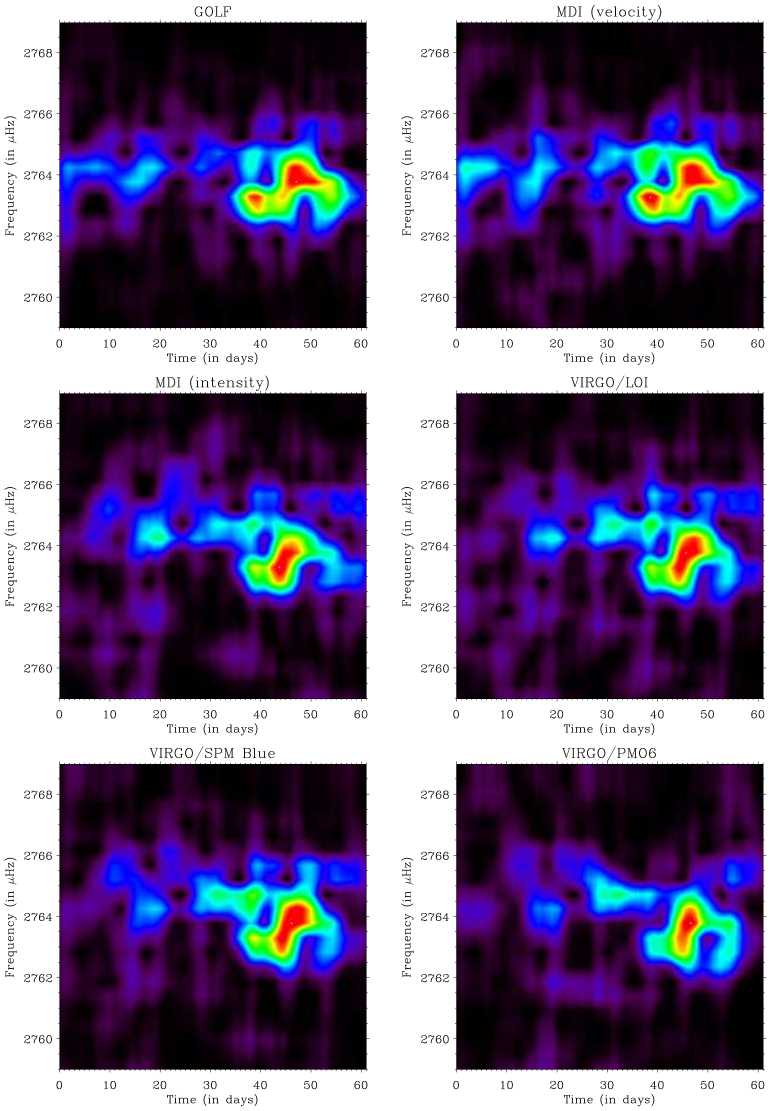


Fig. 7. Wavelet analysis of the $l$=0 $n$=19 mode for the different SOHO instruments. This analysis was performed with Lorentzian wavelets of full width at half maximum of 1$\mu$Hz, corresponding to a 5.1-day resolution in time. The apparent synchronicity of the excitation of this mode on day 48 and the passage of a sunspot (see Fig. 1) may be purely coincidental. It does not occur for other modes.

in different colors. The channels with the longest effective wavelengths (SPM Red, PMO6 and MDI) give higher frequencies (+0.05 $\mu$Hz with uncertainties of 0.03 and 0.02 $\mu$Hz for $l = 0, 1$, respectively) than the green channel of the SPM and the LOI. The comparison between the velocity measurements

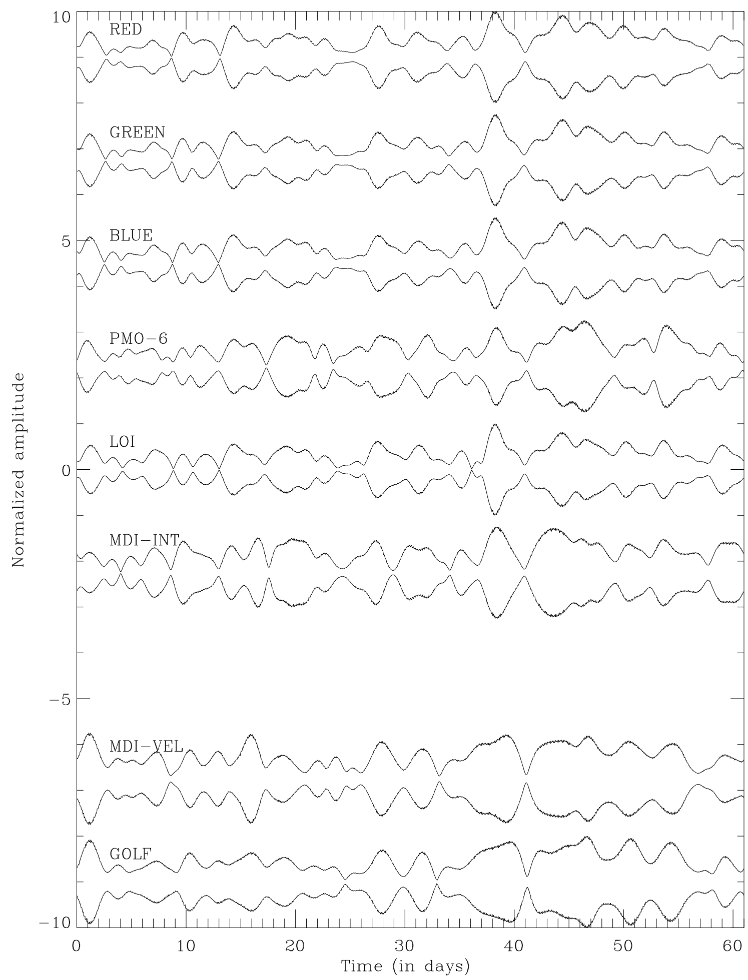


Fig. 8. Amplitude of the $l = 0, n = 19$ mode as a function of time for the various instruments. The envelope of the amplitude was extracted from the mode time series using a Hilbert transform. The mode time series was derived by computing the inverse Fourier transform of a spectrum filtered around a p mode with a gaussian window of width 10-$\mu$Hz.

should properly be made with intensity measurements at these longer effective wavelengths. This results in an average frequency difference between modes seen in intensity and velocity of about -0.15 $\mu$Hz and -0.2 $\mu$Hz for $l = 0, 1$ modes, respectively.

Several causes for these differences can be proposed. They all depend on the basic fact that the observations are caused by the specific response of the solar atmosphere to the standing wave patterns of the modes. The response depends both on the effective formation height in the atmosphere and on whether the observations are made in velocity or intensity. These frequency differences should increase with deteriorating quality of the oscillation cavity.

The changing shift with wavelength may be caused by the difference in formation height of the emergent radiation. At disc center the height difference between the red and green channels of the SPM is a few tens of kilometers. The observed formation height increases toward the limb. The shift caused by a difference in formation height will further increase because the green channel is less weighted towards the limb.

The formation height arguments do not explain the frequency difference between velocity and intensity, since the mode frequencies shift in the *opposite* direction with formation height. The formation heights of the lines where the velocity is measured are a few hundred kilometers above the green channel.

Since we observe the p modes indirectly, through the response of the atmosphere, the difference could be attributed to an effect of the observed atmosphere. One of the main effects of the atmosphere on the p modes is to modify the natural line profiles of the modes. For example mode interferences, like those in a Fabry-Perot cavity, can cause a line asymmetry, as reported by Duvall *et al.*(1993) and Kosovichev *et al.*(1997). The frequency differences among the SOHO instruments are in rough agreement with the profiles observed by Duvall *et al.*(1993) for high degree modes: frequencies of p modes derived from intensity observations are higher than those observed in velocity. This is mainly due to line asymmetry effects pulling the mode frequencies in opposite directions (Fig. 5). On the other hand, it is premature to conclude that asymmetries will always have such systematic effects: Nigam *et al.*(1996) showed that the line asymmetry varies with mode frequency and degree.

Another 'side effect' of the frequency shifts is related to structure inversions. Appourchaux *et al.*(1997) reported that there seems to be a systematic difference between their results and the LOWL inversion, as well as with inversions using contemporaneous data from MDI (Kosovichev *et al.*, 1997). These inversion differences may be due to line asymmetries, as suggested by Kosovichev (1996, private communication), that lead to systematic errors in the determination of the frequencies. We hope that by understanding the line asymmetry we will be able to reduce systematic errors and thereby better interpret the results of inversions derived from VIRGO intensity measurements.

## 6. Conclusion

The time series of all three helioseismology instruments agree extremely well with each other. Solar p-mode frequencies show a systematic difference between intensity and velocity. This systematic difference for low $l$ modes is attributed to a line asymmetry that is stronger in intensity and gives higher measured mode frequencies. Fitting p modes with an asymmetrical profile might help reduce the discrepancy, and may produce inversion results from intensity measurements that agree better with those from velocity. The uniformity of the data from the various instruments should be advantageous in identifying g modes.

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