Phases differences and gains between Intensity and Velocity low degree acoustic modes measured by SOHO[1]

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ABSTRACT

Helioseismic instruments aboard SOHO are making possible a more accurate way to investigate the internal structure of the Sun. Due to the different techniques characteristics of these instruments it is possible to measure solar oscillations as variations of the photospheric velocity (GOLF, MDI) or as irradiance and radiance fluctuations (VIRGO,MDI).

Among other advantages to observe solar oscillations simultaneously with different instruments and techniques, the study of velocity and irradiance measurements provides information on non-adiabatic effects in the radiatively cooled solar atmosphere. The thermodynamical properties of the atmosphere determine a phase shift between intensity and velocity (downward positive) oscillations of -90 degrees in the case of an adiabatic atmosphere. In an atmosphere not purely adiabatic the phase shift must be different from this value. In this work we compute the phase differences and gains between intensity and velocity acoustic modes measured by SOHO to quantify the non-adiabactic degree of the solar atmosphere. Finally we compare the observed phase differences with three different theoretical models.

Subject headings: Sun: atmosphere — Sun: Oscillations

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1. INTRODUCTION

The helioseismic instruments onboard SOHO: VIRGO (Variability of solar IRradiance and Gravity Oscillations),GOLF (Global Oscillations at Low Frequencies) and MDI(Michelson Doppler Imager) are obtaining the higher quality data obtained up to now allowing a more accurate way to investigate the internal structure of the Sun. Due to the different techniques used by these instruments, it is possible to measure simultaneously the solar oscillations either as variations in the photospheric velocity (GOLF and MDI) or as intensity fluctuations (VIRGO,MDI). The main objective of this work is to obtain the gain and phase differences between the p-modes measured as intensity and velocity fluctuations and compare them with predictions of several theoretical models to quantify the adiabatic behaviour of the solar atmosphere.

Frölich & van der Raay (1984) measured these phase shift using velocity data obtained from ground observations, the well known MARK-I resonant spectrophotometer set at Observatorio del Teide (Tenerife) since 1976, and intensity data from a stratospheric balloonflight in a very short span of data. Jiménez et al (1990) used the velocity data of the same instrument (MARK-I) and simultaneous intensity observations obtained with two ground stations (Tenerife and San Pedro Mártir,Baja California) with the SLOT sunphotometer (Andersen et al. 1988). These longer time series results agreed well with the former study and yielded to a I-V phase difference between -120 and -130 degrees. In spite of this, two problems were presented. While in the first observation the flight of the balloon was only around 7 hours giving a poor frequency resolution, in the second, the study of low degree p-modes is very dificult due to the high atmospheric noise level in ground-based intensity observations; therefore, it became evident that space intensity observations were needed. In 1988, the cruise phase of the USSR mission to the Martian satellite Phobos offered the opportunity to measure such phase shift using space intensity data of the IPHIR instrument (Fröhlich et al. 1988) aboard PHOBOS. In 1991, Schrijver, Jiménez & Dappen (hereafter IPHIR paper) used these intensity data and the simultaneous velocity data from MARK-I instrument (three periods of one week and one period of three weeks) to obtain the more accurate measurements of the phase shift, -119 $\pm$ 3 degrees, which agreed with previous results within errors. Now with the SOHO mission (Domingo, Fleck & Poland,1995) it is possible to get uninterrupted simultaneous intensity and velocity measurements both from space and improve drastically the calculations of these phase shifts as it has never been possible. In this work we compute the phase differences and gains between I-V low degree p-modes using data of VIRGO(Fröhlich et al. 1995), GOLF (Gabriel et al. 1995) and MDI (Scherrer et al. 1995).

2. INSTRUMENTATION AND OBSERVATIONS

2.1. VIRGO (Intensities)

1. *SPM SunPhotoMeters*

   The perfomance of VIRGO instrument has been already reported by Fröhlich et al (1997a). The VIRGO/SPM comprises 3 sunphotometers at 402 nm (BLUE), 500 nm (GREEN) and 862 nm (RED) that look at the Sun as a star (the formation height for all three is a few tens of Km). The sampling rate of VIRGO/SPM is 60s. The VIRGO sampling has an offset of 30s with respect to the other two SOHO Helioseismic instruments because VIRGO is the only one instrument synchronized to a daily pulse sent everyday at midnight. This daily pulse was synchronized to the Universal Time before 1996 March 27, and then to the Temps Atomique International (TAI) which is 30s apart in the time span used in this work. This timing conditions of VIRGO have obviously been taken into account in the data analysis. The three VIRGO channels of VIRGO/SPM will be referenced in this paper as VIRGO(RED), VIRGO(GREEN) and VIRGO(BLUE).

2. *Total Solar Irradiance (TSI)*

   There are two different absolute radiometers on VIRGO that measure the Total Solar Irradiance (TSI) or also called the "solar constant": DIARAD and PMO6-V (Fröhlich et al. 1997b). The sensitivity of the radiometers goes from 100 nm to 100μm. The DIARAD instrument has a sampling rate of 180s and therefore it is not suitable for p-mode analysis. On the other hand, the PMO6-V is sampled at 60s since a couple of weeks after VIRGO started its operation. This modification from the original mode of operation (Fröhlich et al. 1995) is because the shutter stops working and remains open. Since then, VIRGO uses the PMO6-V covers three times per day to get the dark cavity measurements. As a result, only the PMO6-V is used for the p-mode comparison.The TSI measurements of the VIRGO PMO6-V radiometer will be referenced in this paper as VIRGO(TSI).

3. *Luminosity Oscillation Imager (LOI)*

   The perfomance of the VIRGO/LOI instrument has been reported by Appourchaux et al. (1997). The VIRGO/LOI images the Sun at 500 nm (formation height same as SPM/GREEN) on a 12-pixel photodiode allowing to detect ℓ <8. The sampling rate is 60s being in phase with all the other instruments of VIRGO. The LOI pixel data have been combined to obtain also a signal of the Sun seen as a star. This instrument will be referenced in this paper as VIRGO(LOI).

2.2. MDI (Velocity and Intensity)

The MDI instrument has been described by Scherrer et al. (1995) and its performances reported by Kosovichev et al. (1997). This instrument measures velocity in the Ni I 676.8

nm line using a double Michelson interferometer with a narrow fixed passband Lyot filter. The velocity signal is from filtergrams taken at four wavelengths across the spectral line (the equivalent formation height is 250 to 300 km). The continuum intensity and line depth are computed from these and an additional filtergram at another wavelength. The data used in this work comes from a proxy that matches the pixel size of the LOI in VIRGO (Appourchaux et al., 1997). The 12 LOI scientific pixels are divided each one in different number of bins: the 4 North-South pixels are divided each one in 17 bins, the 4 East-West and the 4 central pixels in 9 bins; the 4 guiding pixels in 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 the 140 non-limb LOI-proxy bins to determine a 'full disk" signal have been averaged. The final sampling rate is 60s. The intensity and velocity measurements of the MDI instrument will be referenced in this paper as MDI(I) and MDI(V) respectively.

2.3. GOLF (Velocity)

GOLF is a resonant scattering spectrophotometer (Gabriel et al. 1995) which measures the line of sight velocity using the Sodium doublet similarly as the IRIS or BISON ground based networks. The GOLF door was definitively opened on 1996 January becoming fully operative by the end of the month. Over the following months, occasional malfunction of its rotating polarizing elements were noticed, which led to the decision of stopping them in a predetermined position and truly non-stop observations began by mid April 1996. Since then, GOLF has been continuosly and satisfactorily operating in a unforeseen mode before launch, which has found to have less limitations than anticipated. The signal then consists of two close monochromatic photometric measurements in a very narrow band (18 m$\mathring{A}$) on the left wing of the Sodium doublet (Gabriel et al. 1997). This signal has been calibrated as velocity and has been proved to have similar nature as other known velocity measurements such as IRIS, BISON etc (Pallé et al. 1998). The sampling of the GOLF data used in this work is also 60s.

2.4. Data sets

For the reasons mentioned just above concerning the GOLF signals we will use firtsly, the time series from 1996 february 19 to 1996 March 19 (before the rotating polarizing elements malfunction started) in which GOLF measured the usual Doppler velocity which we will call in this paper "Ratio" velocity (GOLF(RATIO)).The spectral resolution of these times series is 0.38μHz. We will compare this GOLF time serie with the corresponding VIRGO one, mainly with the green channel to compute phase differences and gains and compare the results with those of the IPHIR paper. In a second step we will use the simultaneous two months time series of VIRGO, GOLF and MDI between 1996 May 24 to 1996 July 24 for a full comparison between all signals with a spectral resolution of 0.19μHz. During this period GOLF measurements correspond to the blue-wing of the Sodium doublet, we will call this velocity "blue wing velocity" (GOLF(BW))(for a full account see Pallé et al. 1998). In phase differences studies the absolute timing is a very important parameter, in fact an error in the timing produce a frequency dependent phase shift, a straight line in the I-V phase diagram whose slope is proportional to the timing error. In all the time series used in this work the absolute timing has been checked and verified very carefully.

3. BIVARIATE SPECTRAL ANALYSIS OF TIME SERIES

This powerful method described in Koopmans (1974) permits to compute the coherence, phase shift and gain between two time series of the same length. It has already been used by several authors (Kendall et al. 1983, Fröhlich & van der Raay 1984, Schrijver et al. 1991). permits to compute the coherence, phase shift and gain between two time series of the same lenght.

Let's A and B be two time series of lenght T and sinA, cosA, sinB, cosB the sine and cosine amplitudes of the spectra for series A and B. The power spectral densities $P_A(\nu)$, $P_B(\nu)$, the co-spectral density $C_{AB}(\nu)$, the quadrature spectral density $q_{AB}(\nu)$ and the complex cross spectral density $P_{AB}(\nu)$ are defined as:

$$P_A(\nu) = \frac{T}{2}[sin^2A(\nu) + cos^2A(\nu)] \tag{1}$$

$$P_B(\nu) = \frac{T}{2}[sin^2B(\nu) + cos^2B(\nu)] \tag{2}$$

$$C_{AB}(\nu) = \frac{T}{2}[sinA(\nu)sinB(\nu) + cosA(\nu)cosB(\nu)] \tag{3}$$

$$q_{AB}(\nu) = \frac{T}{2}[sinA(\nu)cosB(\nu) - sinB(\nu)cosA(\nu)] \tag{4}$$

$$P_{AB}(\nu) = C_{AB}(\nu) - iq_{AB}(\nu) \tag{5}$$

Before computing coherence, phase shift and gains, these bivariate parameters need to be smoothed, the lenght of the smoothing is not too critical but need to be chosen adequately. If it is too short the parameters are noisy from bin to bin and if it is too large the frequency resolution is lost. After some tests varying the lenght of the smoothing we concluded that a smoothing lenght of 3.8 μHz is the best trade-off for the p-mode range.

After apply the smoothing (indicated by <..> in the following equations) to all the above defined parameters of the spectra of all the time series used in this work, the coherence can be computed as :

$$Coh^2_{AB}(\nu) = \frac{< C_{AB}(\nu) >^2 + < q_{AB}(\nu) >^2}{< P_A(\nu) >< P_B(\nu) >} = \frac{| < P_{AB}(\nu) > |^2}{< P_A(\nu) >< P_B(\nu) >} \tag{6}$$

The coherence is the analogue of the linear correlation coefficient between the two time series A and B in linear-regression analysis: C^2_{AB} measures to what degree the series B can be represented as the output of a linear filter whose input is series A, or more precisely, the proportion of the power at a given frequency which can be explained by its linear regression on the other. The phase difference $\Delta\phi_{AB}(\nu)$, and gain $g_{AB}(\nu)$ between series A and B are given by:

$$\Delta\phi_{AB}(\nu) = tan^{-1}(\frac{< q_{AB}(\nu) >}{< C_{AB}(\nu) >}) \tag{7}$$

$$g_{AB}(\nu) = \frac{| < P_{AB}(\nu) > |}{< P_A(\nu) >} \tag{8}$$

and the corresponding errors by:

$$\epsilon_{\Delta\phi_{AB}}(\nu) = sin^{-1}(\sqrt{\frac{1 - Coh^2_{AB}(\nu)}{(2n-2)Coh^2_{AB}(\nu)}} t_{2n-2}(\frac{\alpha}{2})) \tag{9}$$

$$\epsilon_{g_{AB}}(\nu) = \sqrt{\frac{(1 - Coh_{AB}(\nu))^2 g_{AB}(\nu)}{(n-1)Coh_{AB}(\nu)} F_{2,2n-2}(\alpha)} \tag{10}$$

where n is the Equivalent Degrees of Freedom (EDF), $t_{2n-2}(\alpha/2)$ the Student's t-Distribution, $F_{2,2n-2}(\alpha/2)$ the Fisher's F-Distribution and α the confidence level at which the errors are computed. We choose α=0.8 for phase differences errors and α=0.9 for gain errors.

A best defined gain can be computed by dividing the gain by the coherence as in Schrivjer et al. (1991). As in linear regression analysis, the results depend on wether an "x" variable is fitted against "y" variable or viceversa. In fact, the ratio of the slopes (g_{AB} and $1/g_{AB}$) is equal to the square of the correlation coefficient in linear regression, as is also the case here:

$$C^2_{AB}(\nu) = g_{AB}(\nu) g_{BA}(\nu) \tag{11}$$

If the relative errors in both time series are the same a useful slope in linear regression terms is defined as the ratio of the standard deviations in the "x" and "y" directions. In analogy the best fit amplitude ratio is:

$$\Psi_{AB}(\nu) = \sqrt{\frac{g_{AB}(\nu)}{g_{BA}(\nu)}} = \sqrt{\frac{< P_B(\nu) >}{< P_A(\nu) >}} = \frac{g_{AB}(\nu)}{Coh_{AB}(\nu)} \tag{12}$$

Fig.1 shows an example of the bivariate analysis procedure between intensity and velocity time series for a frequency range in the central part of the p-modes spectrum (left pannel) and for a higher frequency one (right pannel).

EDITOR: PLACE FIGURE 1 HERE.

4. INTENSITY-VELOCITY COMPARISONS RESULTS

In this section we compute phase differences and gains between intensity and velocity acoustic modes measured simultaneously by VIRGO, GOLF and MDI. Only I-V p-modes with coherence higher than 50% have been used in the analysis.

4.1. Phase differences using GOLF "Ratio" velocities

As we mentioned in section 2 we will use firtsly the time series between 1996 February 19 to 1996 March 19 in which GOLF was fully operative measuring "Ratio" velocity to compare with the results of the IPHIR paper which were also obtained with the "Ratio" velocity of the MARK-I instrument. The intensity data correspond to the green channel of VIRGO at 500 nm, the same as IPHIR.

The MARK-I instrument uses the Potassium line (KI 769.9 nm) and GOLF uses the Sodium doublet (D1 at 589.6 nm and D2 at 589,0 nm). The difference in the working spectral line is not a problem as it has already been proved using that calibrated "Ratios" obtained simultaneously at both lines; the mean phase difference between solar p-modes of low degree is zero within errors (Pallé et al. 1992) as it is expected for standing waves. Therefore, the phase differences obtained in this work with GOLF Ratio velocities must agree with the ones obtained in the IPHIR paper.

Fig.2 shows the computed I-V phase differences obtained for the VIRGO(GREEN) and GOLF(RATIO) data. The different symbols corresponds to different ℓ (ℓ=0,1,2 and 3). It is clearly seen for the first time a degree dependence of the phase difference going towards smaller values (more negative) when the mode degree increases. Looking at the mean values on the figure insets, this degree dependence increase with ℓ (the difference between ℓ=0,1, ℓ=1,2 and ℓ=2,3 are around 7,14 and 26 degrees respectively). The results of the IPHIR paper are plotted with a dotted line (below 2500μHz) and a full line (above 2500μHz) and they represents the averaged values (Fig.11 on the IPHIR paper) obtained in that work for ℓ=0,1 and 2. The reason for plotting different below and above 2500μHz is that in the IPHIR paper the results below that frequency were argued by the authors because of the low coherence in that frequency range. The average value found in the IPHIR paper was -119$\pm$3 degrees while in the present work, excluding ℓ=3, is -121.28$\pm$1.23 degrees which agrees very well within errors.

EDITOR: PLACE FIGURE 2 HERE.

4.2. Phase differences using GOLF "Blue-wing" velocities

Now we will use the GOLF blue-wing velocity data from 1996 May 24 to 1996 July 24 and the corresponding simultaneous VIRGO (TSI, LOI and GREEN) and MDI intensity data. Fig.3 shows these phase differences. Although the degree dependence is found to be the same as before, the absolute values are lower. In the GOLF time series between 1996 February 19 to 1996 March 19 in which GOLF was fully operative it is possible compute simultaneously "Ratio" and "blue-wing" velocities and compare the phases. In Fig 4 these phase differences are shown and it is clearly seen this small phase shift of around -7 degrees for the whole spectrum which agree with the work of Pallé et al. (1998). Notice also that there is a small degree dependence very probably as a consequence of the intensity like signal leaking into GOLF Blue-wing signal. If we add the average values of Fig.4 to the average values of Fig.3a, we get what would be the phase differences for VIRGO(GREEN)-GOLF(RATIO) obtained from "blue-wing" measurements; the results approximately are: -121,-113,-118,-134,-171 degrees for: "all", ℓ=0, ℓ=1, ℓ=2, ℓ=3 respectively , in perfect agreement with Fig.2. Only ℓ=3 seems a little bit different (around 10 degrees) and it is because in Fig.2 there are ℓ=3 modes with frequencies higher than 3800μHz which have smaller phase differences; notice that values for ℓ=3 in Fig.2 and in Fig.3a, for the frequency range between 2600μHz to 3800μHz are all very similar within errors, aproximately -170 degrees, because the "blue-wing" - "Ratio" phase difference for ℓ=3 is less than 2 degrees (Fig.4).

EDITOR: PLACE FIGURE 3 HERE.

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4.3. Phase differences using MDI Velocity

We have also used the MDI intensity and velocity data together with VIRGO (TSI,LOI and GREEN) to compute phase differences as shown in Fig.5. The results are congruent, although some small differences appear with respect the previous ones. Comparing Fig5a with Fig.2 and the average values therein and taking into account that the intensity data are the same (VIRGO GREEN) and the phase differences between the calibrated "Ratios" obtained simultaneously at Sodium and Potassium lines is zero within errors (Pallé et al. 1992), the more plausible reason of these small differences is the way in which the Doppler shift velocity has been computed. In the next subsection we will discuss further this point.

4.4. Some remarks on the I-V phase differences using different sources of velocity data (GOLF "blue-wing", GOLF "Ratio" and MDI(V))

In Pallé et al.(1998) it is shown that the always named "Ratio" velocity is not a pure Doppler velocity. In that paper it is shown that the phase shift between the measurements of the blue (BW) and red (RW) wings of the Sodium lines used by GOLF is not 180 degrees as it must corresponds to a pure Doppler velocity shift of the line, but 163 degrees. Comparing the blue and red wing measurements with the calibrated "Ratio" velocity the phase difference BW-RATIO and RW-RATIO are around -9 and 8 degrees respectively (for ℓ=0) which yield to the 17 degrees missed to get the required 180 degrees for a pure velocity signal. This explains why we have to substract the average values of Fig.4 (GOLF(BW)-GOLF(RATIO)) to Fig.3a (VIRGO(GREEN)-GOLF(BW)) to obtain the values of Fig.2 (VIRGO(GREEN)-GOLF(RATIO)) as explained in 4.2 (we know how to convert I-GOLF(BW) phase differences in I-RATIO ones). When the GOLF BW signal is compared with the one obtained from a well known ground instrument, MARKI, an identical behavior is obtained as in the case of GOLF ratio yielding to a phase difference GOLF(BW)- MARKI(RATIO) around -9 degrees for the ℓ=0 modes concluding that the ratio measurements of MARKI and GOLF are of the same nature (Pallé et al. 1998). Nevertheless this effect is not yet completely understood, it can be related to the physics of the oscillations which would introduces a small intensity like variation (opacity probably) mixed with the Doppler shift or a distortion of the line profile. When computing the calibrated "Ratio" velocities, this effect remains in some degree and we are , obviously interested to know precisely the magnitude of this effect or at least have some idea of the precision of observed I-V phase differences. Comparing Fig.2 (VIRGO(GREEN) -GOLF(RATIO)) with Fig.5a (VIRGO(GREEN)-MDI(V)) we see differences around -4, -7, -4 and -7 degrees for $< all >$, ℓ=0, ℓ=1, ℓ=2 respectively (for ℓ=3 is higher due to the lack of points in Fig.5 at high frequencies as explained in 4.2). Assuming that the "Ratio" velocity measurement is not a pure Doppler shift and taking into account that the way in which the MDI velocity is computed is different to the "Ratio" one and between both I-V phase difference diagrams (Fig.2 and Fig.5a) there is a mean difference of around 5 degrees, this "contamination" seems to be very small and we can select a value around 5 degrees as the uncertainty of the computed I-V phase differences due to this unknow effect.

EDITOR: PLACE FIGURE 5 HERE.

4.5. Amplitude gains

The best amplitude gains between p-modes observed in intensity (VIRGO GREEN) and velocity (MDI, GOLF "blue-wing" and GOLF "Ratio") have also been computed as described in chapter 3 (Ψ) and plotted in Fig.6.

The more interesting feature is contained in Fig.6a corresponding to the gain of VIRGO(GREEN) and GOLF(RATIO) velocity, in which we compare with the results of IPHIR paper (dotted below 2500μHz and full above that value as we explained before) which have been divided by 1.4 which is the gain factor between the solar radial velocity measured by the Sodium and Potassium resonant scattering spectrophotometers (Pallé et al. 1992). The small hump around 4100 μHz in the IPHIR data is not observed now and the increase in the gain below 2500μHz is found to be somewhat lower with SOHO data.

The black dots in Fig.6 represent the gain of the noise computed between the p-mode groups which is higher than the p-mode gains (the error bars of the noise gain have not been plotted to avoid confusion because they are , obviously, large). It is interesting to note that below 2500μHz the noise gain is also higher that the p-modes ones indicating that the "small" increase of the p-mode gain below this frequency seems to be real. In conclusion, it can be said that the general trend of the p-mode gains is a fairly weak variation with frequency although below 2200μHz the background noise in intensity measurements is too high being probably responsible for the small increase .

EDITOR: PLACE FIGURE 6 HERE.

5. INTENSITY-INTENSITY COMPARISONS RESULTS

In this chapter we compute phase differences and gains between acoustic modes measured as intensity variations at different wavelengths obtained by VIRGO(BLUE,GREEN,RED,TSI) and MDI(I). The VIRGO(LOI) have not been included because the observations are equivalent to the VIRGO(GREEN) ones. Only I-I p-modes with coherence higher than 50% have been used in the analysis.

5.1. Phase differences

The phase differences between intensity p-modes measured by SOHO are plotted in Fig.7. We have used the Blue,Green and Red channel of VIRGO SPM, the TSI of VIRGO radiometers and intensity data of MDI. We expect a null mean value for these phase differences because they are standing waves as measured by several authors (Isaak et al. 1989, Jiménez et al. 1990, Pallé et al. 1992). Looking Fig 7 some interesting features appear. In Fig.7a and 7d the phase differences are zero within errors, the wavelenghts of these data are 402 nm (VIRGO BLUE) ,500 nm (VIRGO GREEN) and 678.8 nm (MDI). The phase differences between the VIRGO(GREEN) and VIRGO(RED) are clearly non-zero above 2500μHz showing a frequency and degree dependence (Fig.7b). The phase difference starts being zero up to 2500μHz, decrease at a minimum around 3600μHz and increase again. This frequency dependence seems to be the same for ℓ=0 and ℓ=1, less noticeable for ℓ=2 and practically flat for ℓ=3. This feature was previously noted in the IPHIR paper (see Fig4 of that paper) although no degree dependence was detected (ℓ=3 was not observed in the IPHIR data).The frequency dependence was treated as linear in the IPHIR paper and fitted the straight line: $\Delta\phi_{GR} = -22\nu(mHz) + 56$ degrees. If we use this model in our linear range (2500μHz to 3700μHz) they agree well. This feature seems to be a characteristic of the infrared range. In Fig 7c where the phase differences between VIRGO(GREEN) and the Total Solar Irradiance (TSI) are plotted, this feature is also observed although less clear than before; as the absolute radiometers are based in the measurements of the heat flux (Fröhlich et al. 1995) they are sensitive to a wide range of wavelenghts (from 100nm to 100μm) including optical and infrared ranges. If as we mentioned just above this feature seems to be a infrared characteristic, what we observe in Fig.7c is expected.

EDITOR: PLACE FIGURE 7 HERE.

5.2. Amplitude gains

The amplitude gains between VIRGO (BLUE,GREEN,RED,TSI) and MDI intensity are shown in Fig.8 refered to the VIRGO GREEN channel. The gains of Fig 8a (VIRGO RED /VIRGO GREEN) agrees with the result of IPHIR paper. A slight increase of the gain with frequency is observed. In the IPHIR paper it was described by $\Psi_{GR} = 0.045\nu(mHz) + 0.4$ which agrees with our results. For the VIRGO(BLUE)/VIRGO(GREEN) gains this slight increase is not observed (Fig.8b) but it is enlarged for the VIRGO(TSI)/VIRGO(GREEN) results (Fig.8c) and even for MDI(I)/VIRGO(GREEN) gains (Fig.8d) althought in this case it is not too much significative because there are only 3 points at high frequencies with very large errors bars. It seems that again an effect related to the infrared range is observed in the results.

EDITOR: PLACE FIGURE 8 HERE.

6. COMPARISON BETWEEN THE OBSERVED I-V PHASE DIFFERENCES AND THEORY.

We have seen that the phase differences obtained in this work are in agreement with previous ones and yield values different of -90 degrees. With SOHO observations it has also been possible to observe a degree dependence for the I-V phase differences. In this chapter we use a numerical code (we will call it "model 1") according to the approach of Marmolino & Severino (1991) to compare with our observational results. The model assumes that the unperturbed atmosphere is plane parallel, isothermal, in hydrostatic equilibrium (that implies an exponential stratification in density and pressure) and the effect of the wave radiative damping is taken into account with the Newtonian cooling approximation by means of a constant radiative damping time t_R. This code produces T-V phase differences for ℓ=1 considering upward positive velocities (Marmolino & Severino 1991).

Before any comparisons two points need to be clarified. First, the code uses temperature perturbations and we observe intensity ones. Usually I is taken as proxy of T. To verify this, some computations of the I-V phase differences from theoretic waves and radiative transfer models have been done. These preliminary calculations indicate that I is a good proxy of T except close to the f-mode (Severino, Straus & Jefferies 1998). Second, in order to make uniform the conventions and notations used in the phase differences studies, Masiello & Marmolino (1998) suggest to use the notation which attributes positive values to the phase differences when the intensity perturbation leads the velocity perturbation, taken positive away from the Sun. Also the code we have used to compute theoretical phases differences has this notation. For this reason we add 180 degrees to our observed phase differences before comparing with theory.

In Fig.9 the results of the model are plotted (dashed thick lines) together with the observational results. The model has been computed for a small value of the horizontal wavenumber corresponding to ℓ=1 and for T=5000 K and T=6000 K, being both results very similar, for this reason only the results corresponding to T=5000 K have been plotted in Fig.9 to avoid confusions. The calculations have been done for three values of the damping time, from bottom to top in Fig.9: $t_R = 10^5 s$ (essentially adiabatic), 50 s and 1s (close to isothermal). The observational results are the ones of Fig.2 (the uncertainty of 5 degrees explained in 4.3 doesn't change the general trend of the comparisons presented in this section) corresponding to VIRGO(GREEN) intensity and GOLF(RATIO) velocity plotted as different thin lines for different mode degrees ℓ=0,1,2 and 3 in which, as mentioned in chapter 4.1 we observe a degree dependence of the phase differences.

There is a general discrepancy between the model and the observations. The computed

T-V values (proxi for I-V) are 90 degrees for the adiabatic case and they become much greater than 90 degrees if a short damping time is present, instead the observed values are always lower than 90 degrees and they become much lower going from ℓ=0 to ℓ=3. The dependence of the I-V phase differences with the degree ℓ is difficult to explain. We don't think that it could be due to changes in the radiative damping time. Radiative damping is a local effect, and it would be expected that oscillations with different low degree ℓ observed at the same atmospheric level experience the same radiative damping time.

On the other hand, a possible candidate to explain the ℓ-dependence is the solar background, in particular if the I-V phase differences is lower for background than for p-modes and the contribution of the background to the phase increases with ℓ. The contribution of the background might explain also the fact that the T-V phase differences computed with this model are higher than observed. We have also computed the mean phase differences of the background between p-modes groups and we have included these values in Fig.9 (squares). In fact they are lower than the ones of p-modes and this seems to support the possibility that the solar background could take part on these effects.

Other more plausible reason to explain the discrepancy between theory and observations is the convection, which is not included in "model 1". Gough (1985) computed the effects of turbulent pressure as well as of the modifications in the structure of the super-adiabatic region due to physical changes in the convection process. We will call this model, "model 2" and it is plotted with dash-dot-dash thick line in Fig.9 (we also added 180 degrees). This "model 2" yields results with strong deviations from the 90 degrees adiabatic value and being closer to the observations but still not good (significantly lower than observations).

We will compare with a third model ("model 3") by Houdek, Balmforth and Christensen-Dalsgaard (1995) which includes convective dynamics in the calculations according to a time dependent mixing-length formulation. These theoretical results (adding 180 degrees also) are shown in Fig.9 for three different sets of mixing length parameters (full thick lines). The results of this model go in the right direction as "model 2" but still the agreement with observations is not perfect (significantly higher than observations).

Several points must be taken into account when computing non-adiabatic effects on the waves:

i) Fluctuations of the super-adiabatic temperature gradient in the low photosphere induced by oscillations.

ii) Radiative damping of the wave temperature fluctuations in the low photosphere layers.

iii) Turbulent pressure associated to convection.

iv) Radiative transfer to pass from the wave temperature and pressure perturbations to the observed intensity fluctuations.

v) Integration of intensity over the disk to account for center-to-limb spatial distribution of the wave perturbations.

vi) The influence of a background having phase differences different to those of the p-modes.

There is not any model computing phase differences for p-modes and including all these points. The non-adiabatic computation of "model 1" accounts for point ii), however this effect is to increase the phase difference above 90 degrees for the non-adiabatic case, in contrast with observations. The "model 2" and "model 3" account for points i) and iii). They found that the 90 degrees phase difference of the adiabatic case decreases in rough agreement with observations although the absolute value doesn't fit the measured phase differences, "model 2" yields to lower values and "model 3" to higher values.

It is suggestive, for example, that if the trends of "model 1" and "model 2" are opposite producing phase differences higher and lower than the 90 degrees for adiabatic conditions, a combination of both models, accounting points i),ii) and iii) , would improve the agreement between theory and observations as well as a combination of "model 2" and "model 3". It would be attractive to see the results of a model including all the six points mentioned above.

EDITOR: PLACE FIGURE 9 HERE.

7. CONCLUSIONS

The phase differences between intensity and velocity acoustic modes measured by the helioseismic instrument aboard SOHO satellite have been measured with a precision never reached up to now.

The general trend of the I-V phase difference diagrams is, at first, a non-adiabatic behaviour (phase differences distinct of -90 degrees) with a slight frequency dependence increasing towards higher frequencies. The mean value of these phase differences is -120 $\pm$ 1.39 degrees (see Fig.2) in perfect agreement with previous observations. Nevertheless and for first time, a mode degree dependence is clearly observed decreasing the phase difference when increasing ℓ (-113.01 $\pm$ 1.64 for ℓ=0, -119.90 $\pm$ 0.98 for ℓ=1, -134.91 $\pm$ 1.81 for ℓ=2 and -161.41 $\pm$ 4.49 for ℓ=3).

When comparing these observationals results with several models it is concluded that models including only radiative damping produces phase differences opposite to the ones observed, and including only turbulent pressure associated to convection and fluctuations of the super-adiabatic temperature gradient produce phase differences in the right direcction but not fitting the absolute values. A combination of all these models could explain the observations although other three effects must be included in the calculations (or at least their influence should be evaluated) :radiative transfer to pass from the wave temperature and pressure perturbations to the observed intensity, integration of intensity over the disk to account for the center-to-limb spatial distribution of the wave perturbations and the influence of the background when computing phase differences.

The "blue-wing" velocity measurements by GOLF have a small contamination which introduce a small phase shift (ℓ dependent) which must be taken into account when computing I-V phase diagrams with these data (see Fig.4). The mean value of the phase difference between GOLF "blue-wing" and GOLF "Ratio" velocities is -7.27 $\pm$ 0.29 degrees and for different ℓ are : -8.67 $\pm$ 0.25 for ℓ=0, -8.11 $\pm$ 0.22 for ℓ=1, -4.54 $\pm$ 0.31 for ℓ=2 and 1.64 $\pm$ 1.31 for ℓ=3.

The "Ratio" velocities conceived up to now as "pure Doppler shifts" are not exactly "pure" as concluded also in Pallé et al. (1998). This introduce an uncertainty around 5 degrees in the I-V phase differences computed in this work.

The I/V amplitude gains obtained in this work show a small increase for frequencies lower than 2500μHz which seems to be real, although the errors are high at those frequencies (the noise gain is always higher than the p-modes gains). Nevertheless the general trend is a weak variation with frequency in the p-mode range with no apparent degree dependence (see Fig.6). These results agree with the previous ones.

When computing the I-I phase differences a null value for wavelengths lower than 677 nm (MDI intensity) are obtained as one can expect for standing waves. Nevertheless when the infrared part of the spectrum ,VIRGO(RED) and VIRGO(TSI) are used, a clear frequency dependence (see Fig7b) is observed also depending with ℓ. The mean value for VIRGO(GREEN) -VIRGO(RED) is -10.53 $\pm$ 0.72 degrees and for the different ℓ are : -12.53 $\pm$ 1.24 for ℓ=0, -12.57 $\pm$ 0.96 for ℓ=1, -6.07 $\pm$ 0.85 for ℓ=2 and 5.9 $\pm$ 1.0 for ℓ=3.

This effect is not yet well understood but can be related to a downward travelling wave or differences in the damping time at different layers of the atmosphere.

The I/I amplitude gains obtained in this work show a weak variation with frequency, increasing slightly to higher frequencies when infrared measurements take part in the observations (see Fig.8). This effect is enlarged (although high errors are present) when Total Solar Irradiance (TSI) measurements are used. Again an effect related to the infrared is observed as mentioned above.

All three instruments benefit from the quiet and well run SOHO platform built by Matra-Marconi Space. SOHO is an international collaboration programme of the European Space Agency and the national Aeronautics Space Administration. We thank G. Houdek for providing the model data. VIRGO,GOLF and MDI are cooperative efforts of many individuals scientists and engineers at several institutes in Europe and USA to whom we are deeply acknowledged. This work have been done under the Spanish grant 95-0028-C from DGICYT.

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Fig. 1.— Two examples of the bivariate spectral analysis between intensity and velocity time series. From bottom to top: Intensity amplitude spectrum, Velocity amplitude spectrum, coherence, phase difference and gain. Left and right pannels corresponds to two different frequency intervals in the p-modes range.

Fig. 2.— Phase differences between the VIRGO(GREEN) channel and GOLF(RATIO) velocity p-modes for different degrees ℓ=0,1,2 and 3 (averages denoted by <..>) and compared with the IPHIR results.

Fig. 3.— Phase differences between intensities and GOLF "Blue-wing" (GOLF(BW)) velocity p-modes for different degrees ℓ=0,1,2 and 3 (averages denoted by <..>). The intensity signals of VIRGO(GREEN),VIRGO(LOI),VIRGO(TSI) and MDI(I) have been used (from bottom to top).

Fig. 4.— Phase differences between the GOLF "Blue-Wing" velocity and GOLF "Ratio" velocity for different degrees ℓ=0,1,2 and 3 (averages denoted by <..>) in the time span in which both were available (1996 February 19 to 1996 March 19).

Fig. 5.— Phase differences between intensities and MDI velocity p-modes for different degrees ℓ=0,1,2 and 3 (averages denoted by <..>). The intensity signals of VIRGO(GREEN),VIRGO(LOI),VIRGO(TSI) and MDI(I) have been used (from bottom to top).

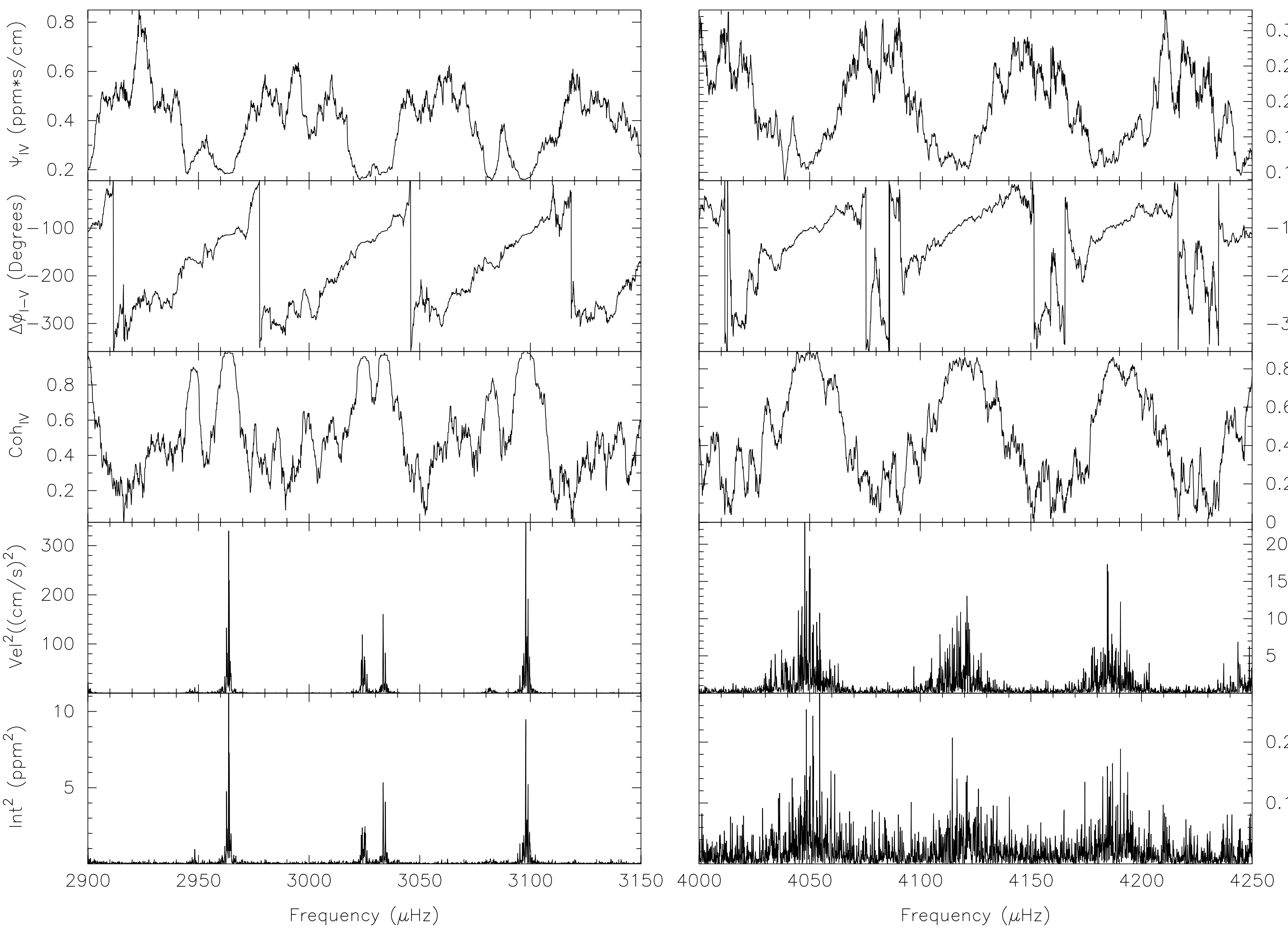
Fig. 6.— Gains between VIRGO(GREEN) channel and GOLF (RATIO), GOLF("Blue-Wing") and MDI(V) velocities (from bottom to top) and for different degrees ℓ=0,1,2 and 3 (averages denoted by <..>). In all of them the gain of the noise between p-modes group have been plotted. In (a) the results have been compared with IPHIR. See text.

Fig. 7.— Phase differences between VIRGO(GREEN) and VIRGO (BLUE,RED,TSI) and

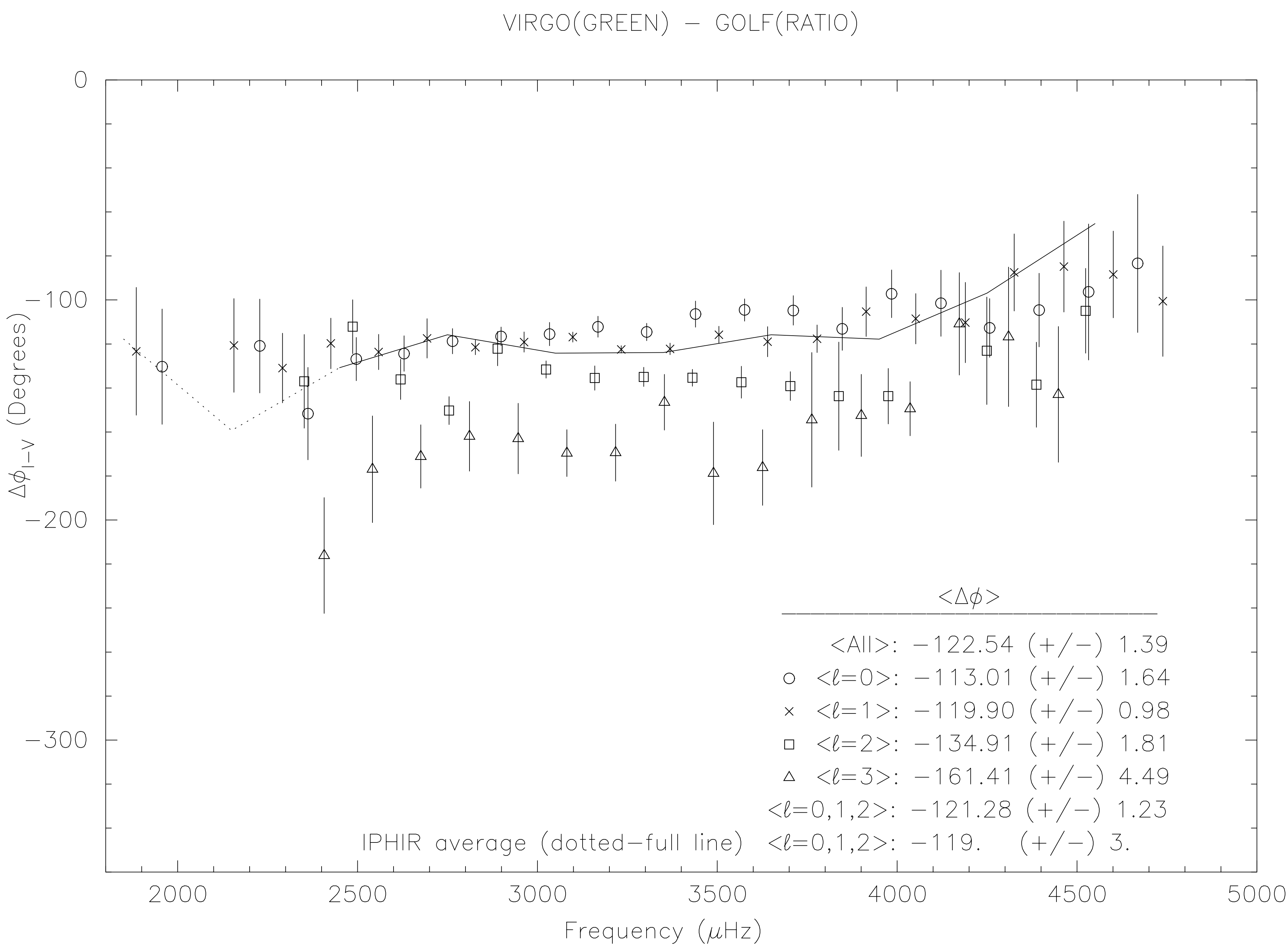
MDI(I) intensities (from bottom to top) and for different degrees ℓ=0,1,2 and 3 (averages denoted by <..>).

Fig. 8.— Gains of VIRGO(RED,BLUE,TSI) and MDI(I) related to VIRGO(GREEN) (from bottom to top) and for different degrees ℓ=0,1,2 and 3 (averages denoted by <..>).

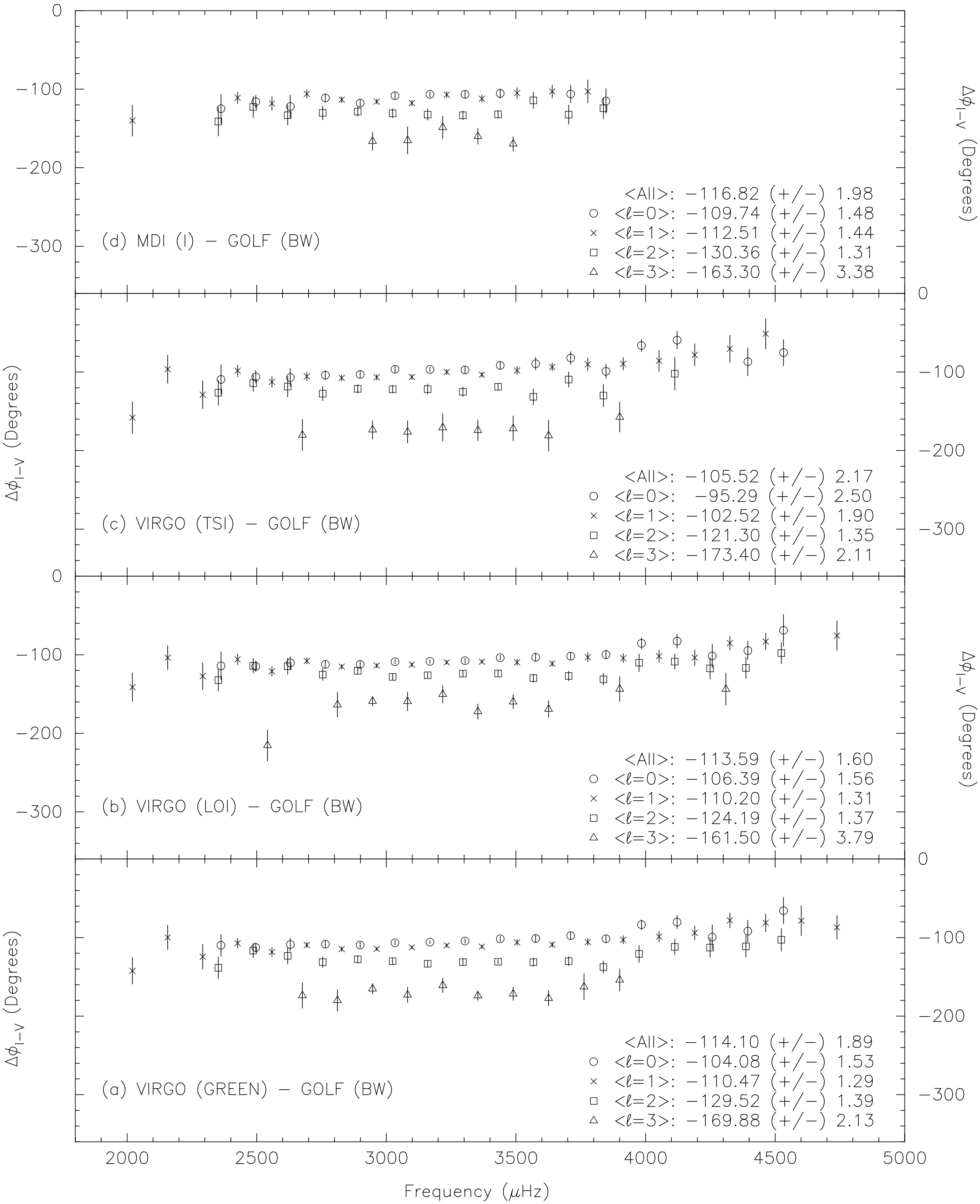
Fig. 9.— Comparisons between I-V phase differences obtained in this work and theoretical equivalent computation using the same notation. The thick dashed lines corresponds to "model 1" for three different damping times,from bottom to top: $t_R = 10^6 s$ (adiabatic),$t_R = 50s$, and $t_R = 1s$(close to isothermal). The thick dash-dot-dash line corresponds to "model 2" and the thick full lines corresponds to "model 3" for three different sets of mixing lenght parameters. The observed phases differences are indicated by different thin lines for different degrees ℓ=0,1,2 and 3 and corresponds to the results of Fig.2. The squares represent the phase differences between p-modes groups.

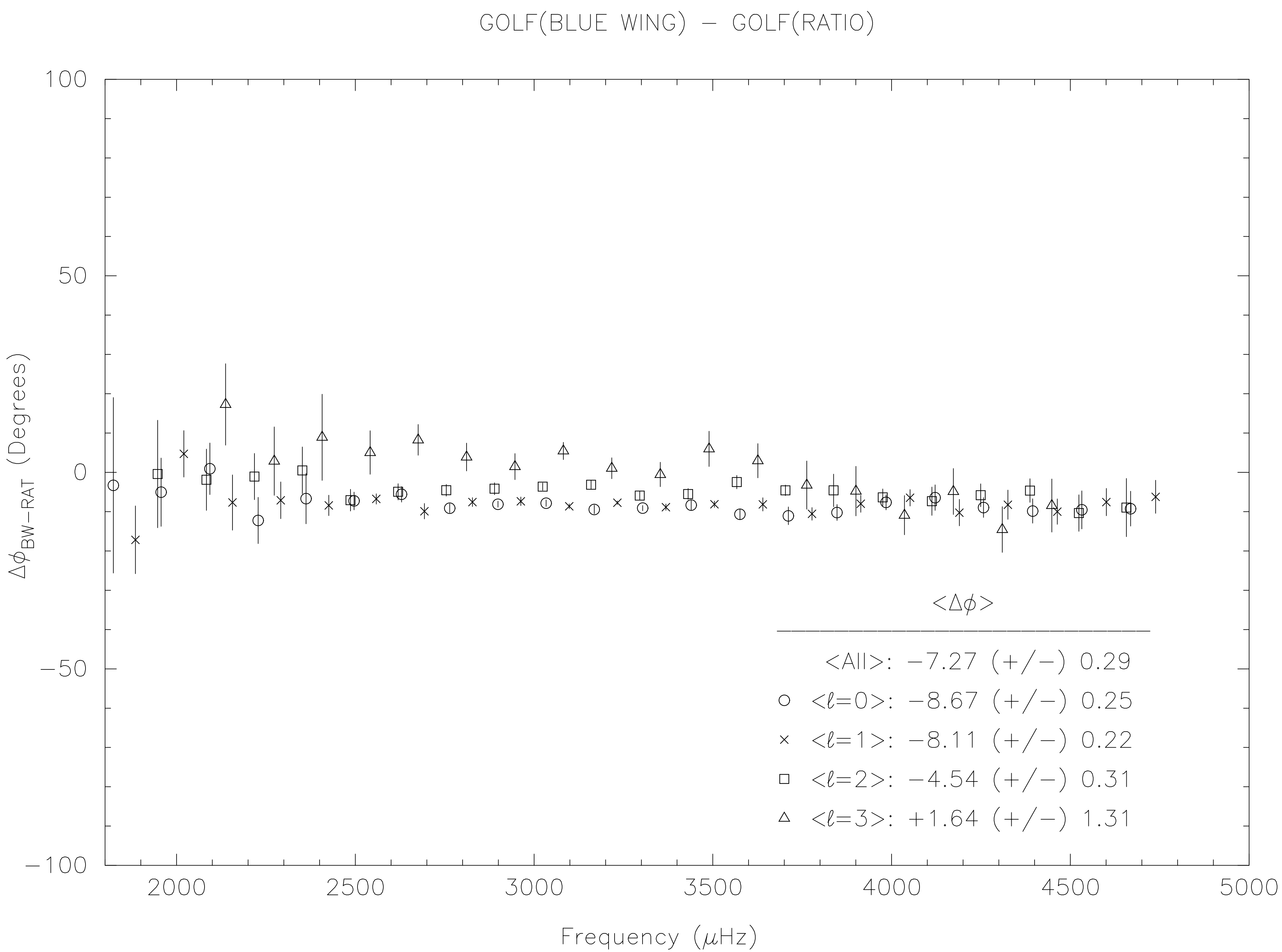


Ψ_{IV} (ppm*s/cm)
$\Delta\phi_{I-V}$ (Degrees)
Coh_{IV}
$Vel^2((cm/s)^2)$
Int^2 (ppm^2)
Frequency (μHz)
Frequency (μHz)

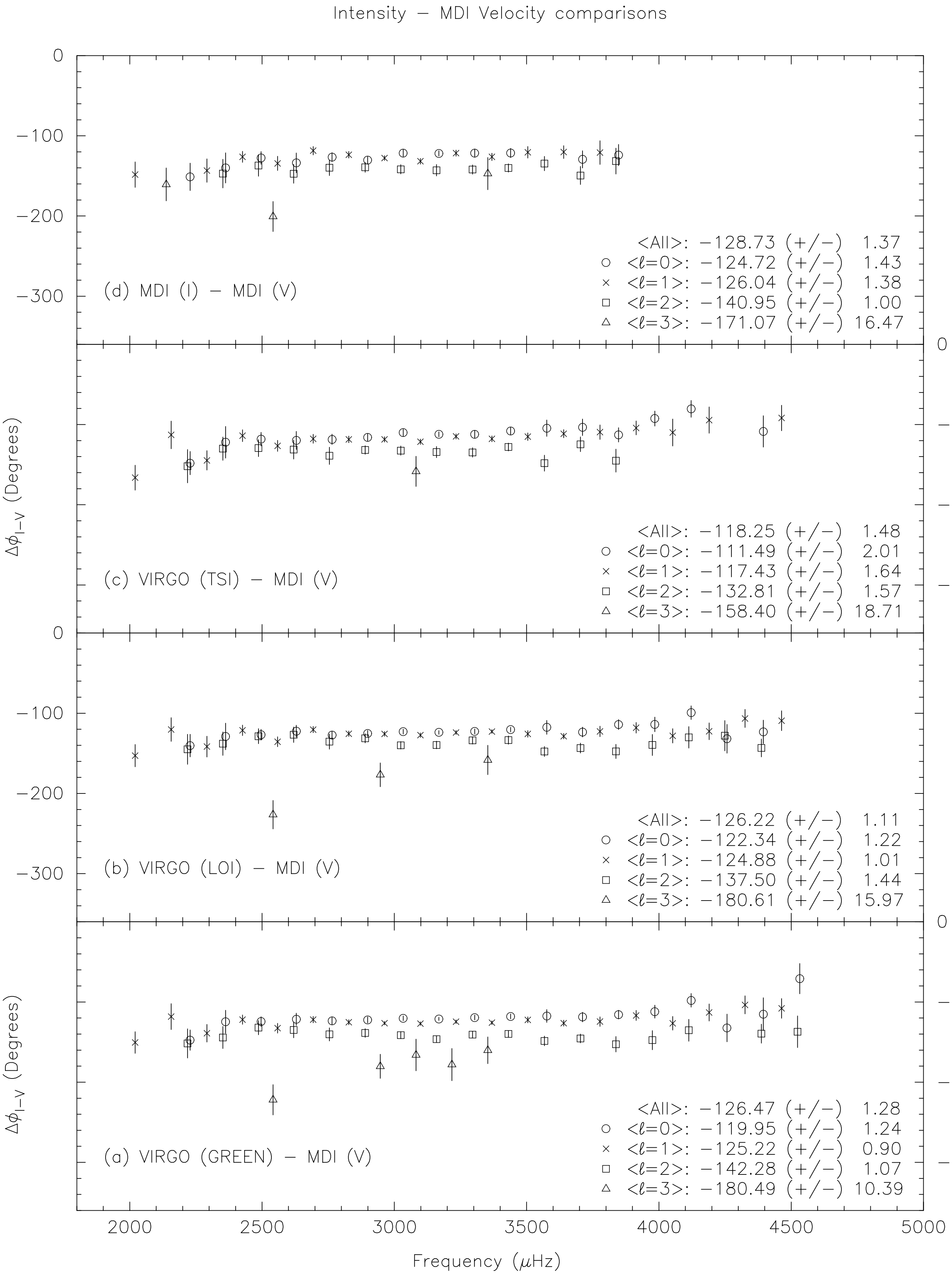

VIRGO(GREEN) – GOLF(RATIO)
$\Delta\phi_{I-V}$ (Degrees)
0
−100
−200
−300
2000
2500
3000
3500
4000
4500
5000
Frequency (μHz)
$<\Delta\phi>$
<All>: −122.54 (+/−) 1.39
$<\ell=0>$: −113.01 (+/−) 1.64
$<\ell=1>$: −119.90 (+/−) 0.98
$<\ell=2>$: −134.91 (+/−) 1.81
$<\ell=3>$: −161.41 (+/−) 4.49
$<\ell=0,1,2>$: −121.28 (+/−) 1.23
IPHIR average (dotted–full line) $<\ell=0,1,2>$: −119. (+/−) 3.

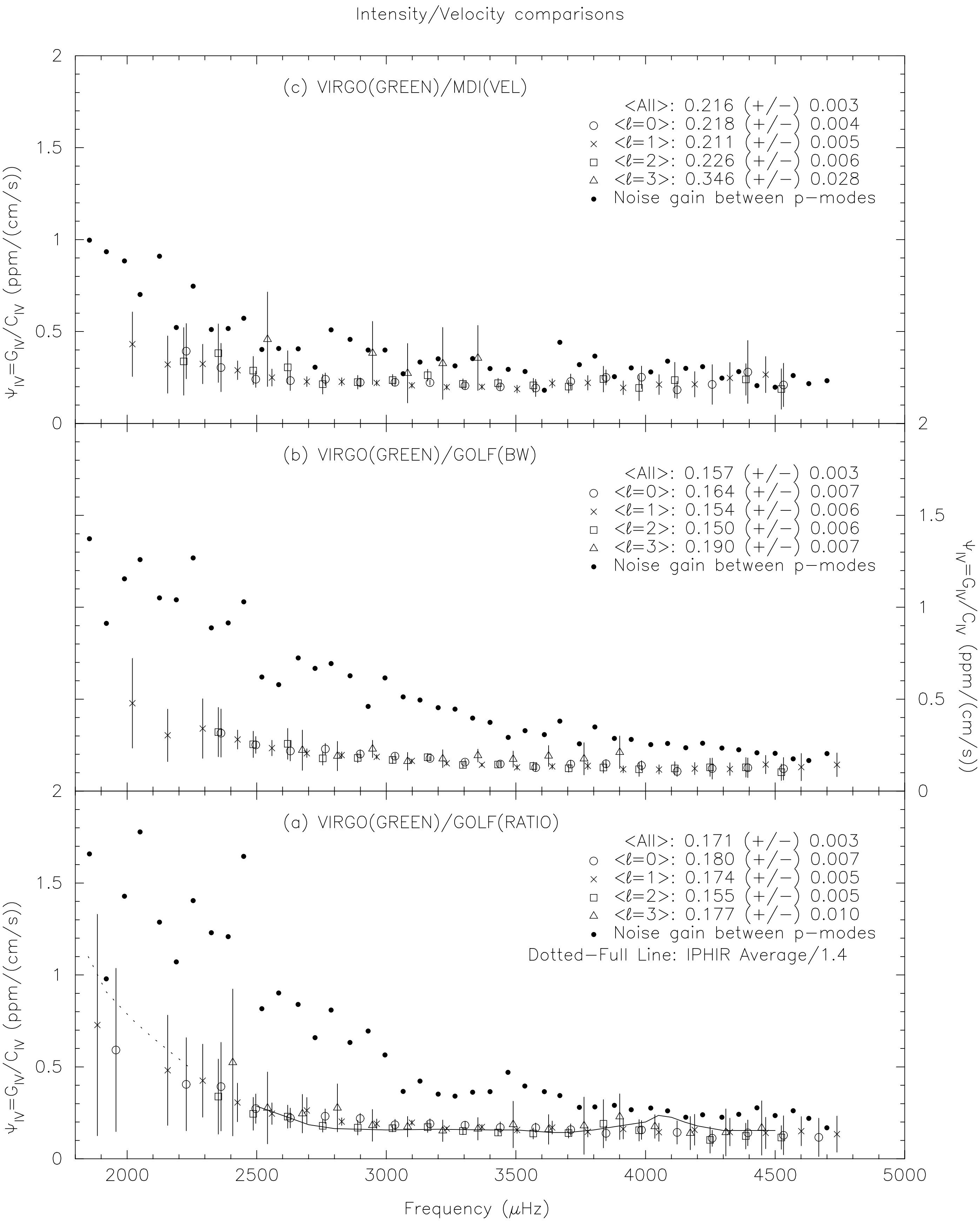
Intensity – Blue Wing (BW) Velocity comparisons





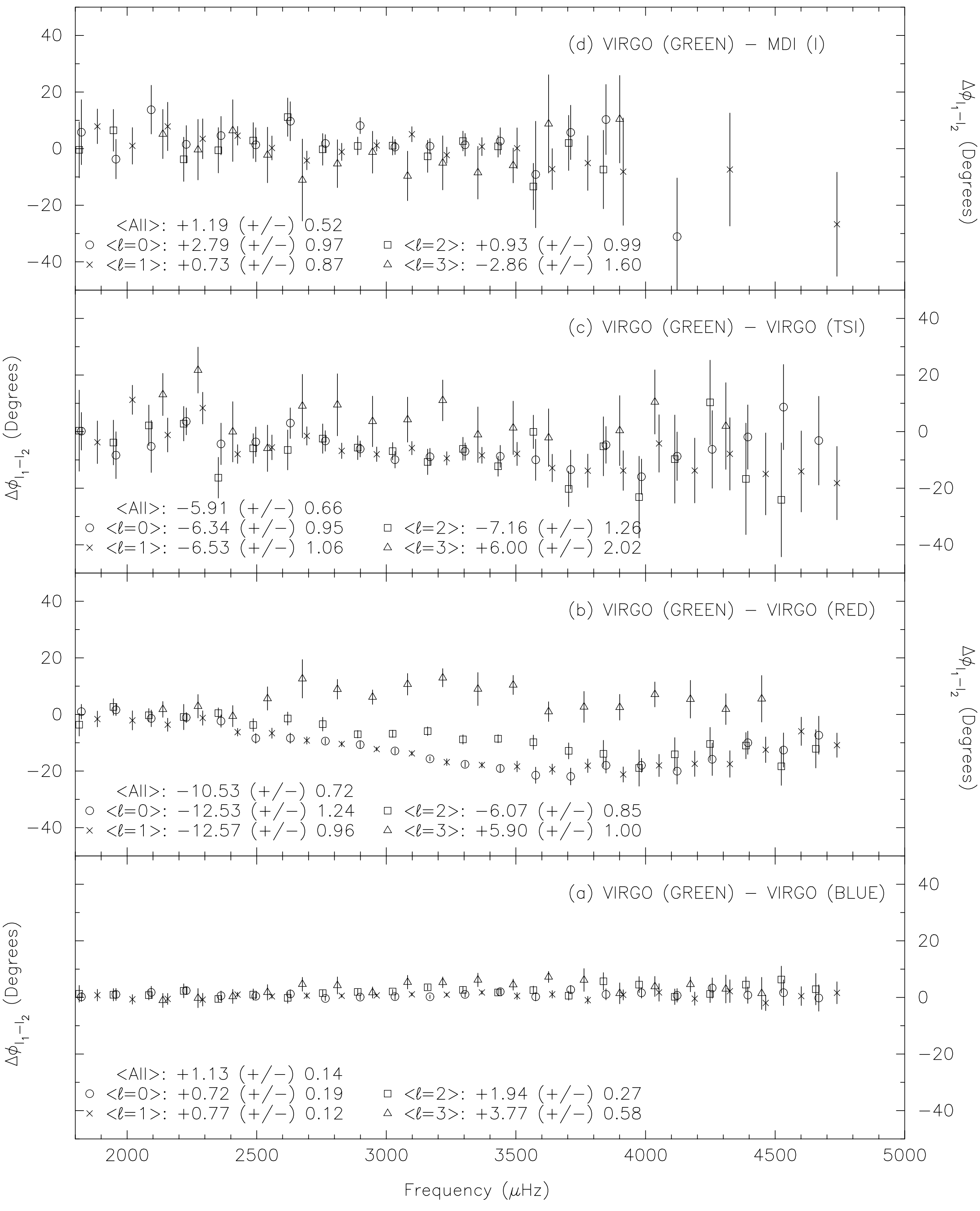
GOLF(BLUE WING) − GOLF(RATIO)
100
50
0
−50
−100
$\Delta\phi_{BW-RAT}$ (Degrees)
2000
2500
3000
3500
4000
4500
5000
Frequency (μHz)
<$\Delta\phi$>
<All>: −7.27 (+/−) 0.29
<ℓ=0>: −8.67 (+/−) 0.25
<ℓ=1>: −8.11 (+/−) 0.22
<ℓ=2>: −4.54 (+/−) 0.31
<ℓ=3>: +1.64 (+/−) 1.31

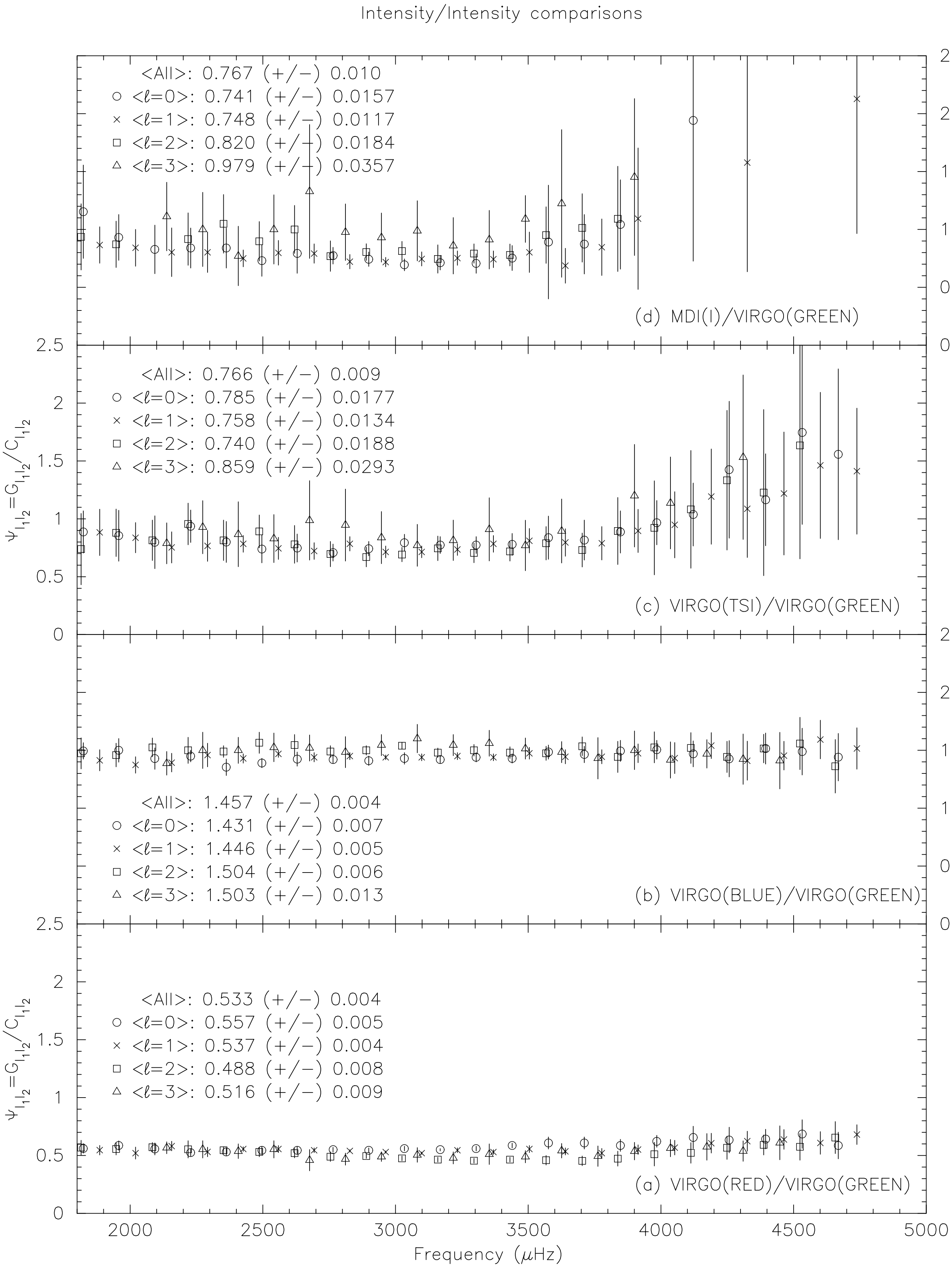

Intensity − MDI Velocity comparisons
(d) MDI (I) − MDI (V)
<All>: −128.73 (+/−) 1.37
<ℓ=0>: −124.72 (+/−) 1.43
<ℓ=1>: −126.04 (+/−) 1.38
<ℓ=2>: −140.95 (+/−) 1.00
<ℓ=3>: −171.07 (+/−) 16.47
(c) VIRGO (TSI) − MDI (V)
<All>: −118.25 (+/−) 1.48
<ℓ=0>: −111.49 (+/−) 2.01
<ℓ=1>: −117.43 (+/−) 1.64
<ℓ=2>: −132.81 (+/−) 1.57
<ℓ=3>: −158.40 (+/−) 18.71
(b) VIRGO (LOI) − MDI (V)
<All>: −126.22 (+/−) 1.11
<ℓ=0>: −122.34 (+/−) 1.22
<ℓ=1>: −124.88 (+/−) 1.01
<ℓ=2>: −137.50 (+/−) 1.44
<ℓ=3>: −180.61 (+/−) 15.97
(a) VIRGO (GREEN) − MDI (V)
<All>: −126.47 (+/−) 1.28
<ℓ=0>: −119.95 (+/−) 1.24
<ℓ=1>: −125.22 (+/−) 0.90
<ℓ=2>: −142.28 (+/−) 1.07
<ℓ=3>: −180.49 (+/−) 10.39
Δφ_{I−V} (Degrees)
Frequency (μHz)
0
−100
−200
−300
2000
2500
3000
3500
4000
4500
5000

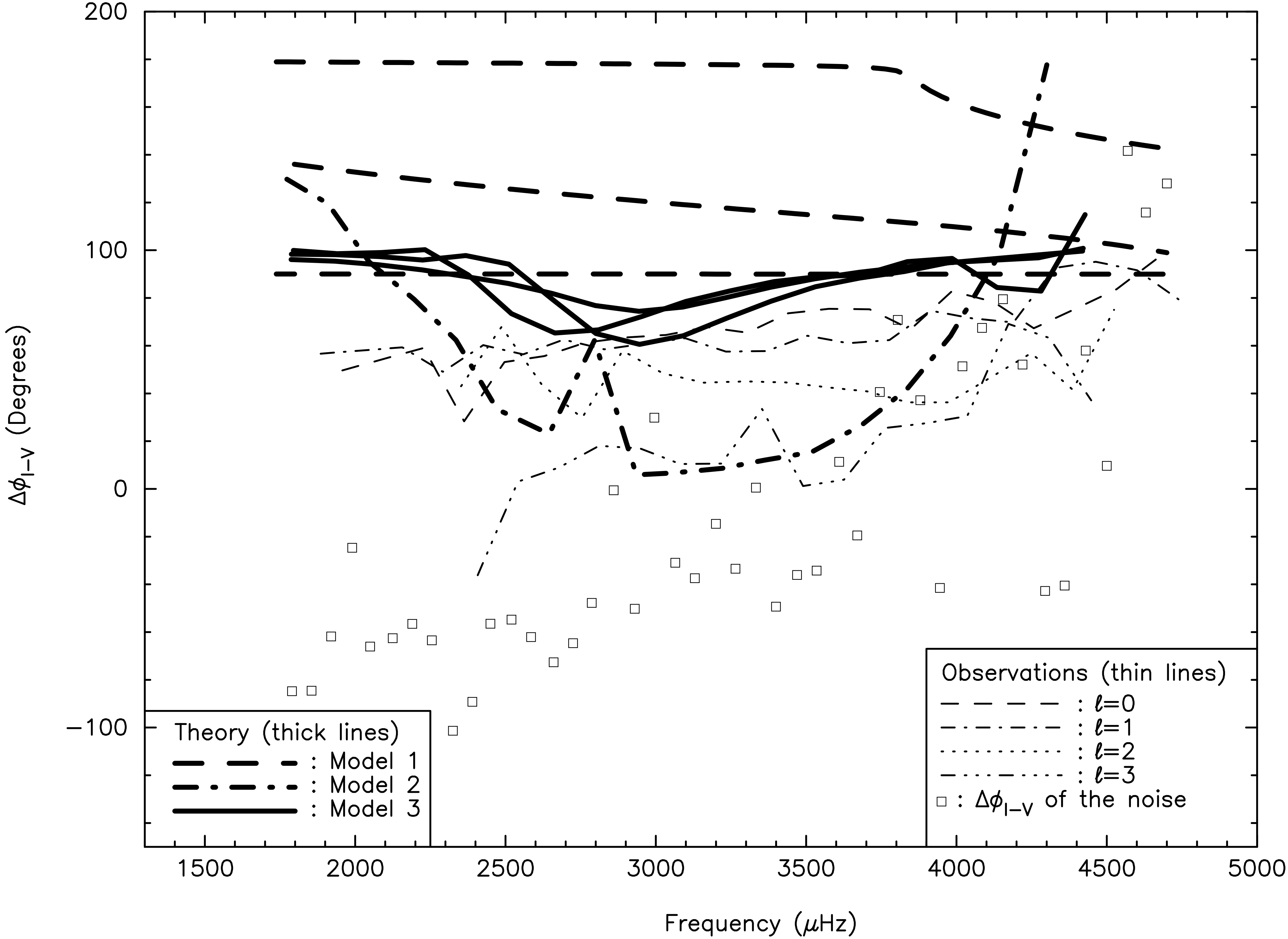


Intensity/Velocity comparisons
(c) VIRGO(GREEN)/MDI(VEL)
<All>: 0.216 (+/−) 0.003
<ℓ=0>: 0.218 (+/−) 0.004
<ℓ=1>: 0.211 (+/−) 0.005
<ℓ=2>: 0.226 (+/−) 0.006
<ℓ=3>: 0.346 (+/−) 0.028
Noise gain between p−modes
(b) VIRGO(GREEN)/GOLF(BW)
<All>: 0.157 (+/−) 0.003
<ℓ=0>: 0.164 (+/−) 0.007
<ℓ=1>: 0.154 (+/−) 0.006
<ℓ=2>: 0.150 (+/−) 0.006
<ℓ=3>: 0.190 (+/−) 0.007
Noise gain between p−modes
(a) VIRGO(GREEN)/GOLF(RATIO)
<All>: 0.171 (+/−) 0.003
<ℓ=0>: 0.180 (+/−) 0.007
<ℓ=1>: 0.174 (+/−) 0.005
<ℓ=2>: 0.155 (+/−) 0.005
<ℓ=3>: 0.177 (+/−) 0.010
Noise gain between p−modes
Dotted−Full Line: IPHIR Average/1.4
$\Psi_{IV}=G_{IV}/C_{IV}$ (ppm/(cm/s))
Frequency (μHz)

Intensity – Intensity comparisons




Intensity/Intensity comparisons
<All>: 0.767 (+/−) 0.010
<ℓ=0>: 0.741 (+/−) 0.0157
<ℓ=1>: 0.748 (+/−) 0.0117
<ℓ=2>: 0.820 (+/−) 0.0184
<ℓ=3>: 0.979 (+/−) 0.0357
(d) MDI(I)/VIRGO(GREEN)
<All>: 0.766 (+/−) 0.009
<ℓ=0>: 0.785 (+/−) 0.0177
<ℓ=1>: 0.758 (+/−) 0.0134
<ℓ=2>: 0.740 (+/−) 0.0188
<ℓ=3>: 0.859 (+/−) 0.0293
(c) VIRGO(TSI)/VIRGO(GREEN)
<All>: 1.457 (+/−) 0.004
<ℓ=0>: 1.431 (+/−) 0.007
<ℓ=1>: 1.446 (+/−) 0.005
<ℓ=2>: 1.504 (+/−) 0.006
<ℓ=3>: 1.503 (+/−) 0.013
(b) VIRGO(BLUE)/VIRGO(GREEN)
<All>: 0.533 (+/−) 0.004
<ℓ=0>: 0.557 (+/−) 0.005
<ℓ=1>: 0.537 (+/−) 0.004
<ℓ=2>: 0.488 (+/−) 0.008
<ℓ=3>: 0.516 (+/−) 0.009
(a) VIRGO(RED)/VIRGO(GREEN)
$\Psi_{I_1I_2}=G_{I_1I_2}/C_{I_1I_2}$
Frequency (μHz)
2000
2500
3000
3500
4000
4500
5000
0
0.5
1
1.5
2
2.5


200
100
0
−100
$\Delta\phi_{I-V}$ (Degrees)
1500
2000
2500
3000
3500
4000
4500
5000
Frequency (μHz)
Theory (thick lines)
: Model 1
: Model 2
: Model 3
Observations (thin lines)
: ℓ=0
: ℓ=1
: ℓ=2
: ℓ=3
: $\Delta\phi_{I-V}$ of the noise