REPORT FROM WORKING GROUP SESSION 1:
RESONANT MODE CHARACTERIZATION

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ABSTRACT

A high level of activity has taken place in the topic of the characterization of the solar oscillation modes over the past few years. This rapid pace of activity was evident by the relatively large number of posters (a total of 63) which were assigned to this Working Group Session. Given the large number of such poster papers, the presentations were divided into groups and the first authors of all of the papers within a given group were invited to present synoposes of their results. After each group of oral summaries was completed, we then opened the floor for a discussion of those summaries. Furthermore, because of the time limitations, a set of papers which was originally assigned to this Working Group Session, and which dealt with the problems of treating the asymmetric shapes of the p-mode power spectral peaks and with the asymmetry of the power of the components of the ℓ = 1 multiplets, was moved by mutual agreement with the authors of those papers to Working Group Session 6 for discussion there. In this report we will briefly summarize the recent results which were presented by the authors of the remaining posters to the other attendees at the Working Group Session 1.

Key words: helioseismology; mode physics.

1. INTRODUCTION

The poster papers which we will discuss in this report cover a wide range of topics within the overall heading of the characterization of the resonant modes of solar oscillation. The interest that this topic has generated is evident from the relatively large total of 63 poster papers which were placed into this Working Session by the Scientific Organizing Committee. Given the rather limited amount of time which we had available for the Working Session, we decided in advance to group the papers into five sub-topics in order to better focus the discussions. We then gave each of the principal authors the opportunity of making a brief oral presentation of the most important points of their papers. After all of the authors of a given sub-topic had completed their presentations, we opened the floor for an open discussion of the papers which had just been presented. Once we had completed the presentation and discussion of all of the papers within a sub-topic, we then moved on to discuss the papers in the other sub-topics. The sub-topics which we employed were the following: 1) new techniques of data analysis, 2) recent calibrations of the various instruments, 3) choices of fitting strategies, 4) recent results, and 5) progress reports of various projects. For the remainder of this report we will describe in order the results which were presented in each of these sub-groupings.

2. NEW TECHNIQUES OF DATA ANALYSIS

The analysis of most helioseismic data in the past has been characterized by the fitting of the power spectra of the observed time series (either intensity or velocity data) in the frequency range where the p-mode signal clearly dominates the background (i.e., from 1.5 to 4.5 mHz). Recent observations from both the ground and from space have extended the frequency range for which peaks can be seen to both higher and lower values. At the higher frequencies the increase in linewidth and the decrease in the power of the modes combine to yield an ever diminishing signal-to-background ratio, S/B. On the other hand, at the low frequency portion of the spectrum the p-mode power decreases with decreasing frequency while at the same time the background power increases. The combination of both of these changes yields a S/B ≤ 1. As a consequence of these low values of the S/B, the techniques which have been used in the past are inadequate to detect all of the possible solar signals which might later be identified as oscillatory modes in both the high- and low-frequency domains.

Some of the posters presented in this group addressed this problem by introducing new techniques which seem to be especially suitable for the detection of coherent, persistent signals under such difficult conditions; These techniques included:

- Singular spectrum analysis. This technique is a non-Fourier technique which uses a different set of basis functions than sines and cosines in
an attempt to separate a larger number of signals from the background noise than is possible with traditional Fourier techniques (Varadi et al.). One of the apparent problems of this technique is the need of finding an objective way of separating the “true” peaks from the other, “false” peaks. Another difficulty is the proper assessment of the statistical significance of the peaks that have been selected.

- Filter Diagonalization. This is a second non-Fourier spectral estimator with potentially interesting applications in separating closely-spaced peaks in the presence of a high level of noise. Jones et al. showed its use with synthetic as well as with observed (LOI) data.

- Multi-taper analysis. In multi-taper analysis (Komm et al., paper 2), an average is made of a set of uncorrelated spectra which have been computed from the same original time series but using a set of different orthogonal tapers. The idea of the technique is to obtain an output spectrum which has less variance than does the corresponding single-taper spectrum. From this quieter spectrum a larger number of peaks can be identified. Multi-tapering techniques were extended to two-dimensions and to multiple-segments of a long time series by Fodor & Stark.

- Exact fractions. This technique, widely used in interferometry, finds interesting applications for extracting equispaced signals from a noisy background. Hence, this technique is appropriate for use in the search for the g-mode signature in the asymptotic regime (Pallé et al., paper 1).

- Auto-Regressive (AR) methods. It was also interesting to hear of the application of parametric modeling of the GOLF time series in which a second-order AR process was employed (Mouret et al.).

Efforts were also presented to solve the difficult task of estimating the amount of power which leaks into the peak of a given (n, ℓ, m) mode from its neighboring peaks. The careful computation of the leakage matrices for both the velocity- and intensity-based GONG power spectra was summarized by Hill & Howe. Similar calculations of the leakage matrix for the Fourier transform of the MDI velocity observations were presented in the invited review talk given the same day by Schou. Both methods seek an improved determination of the measured modal frequencies. They are also designed to obtain better estimates of the errors in these frequencies.

With the aim of a better determination of the (ℓ, ν) diagram from ground-based observations, the non-traditional methods of pipeline processing that were described by Didkovsky et al. and by Haneychuk et al. to improve upon the traditional procedures seemed to be promising. An improvement of an order of magnitude in the precision of the determination of the image center co-ordinates and of the orientation of the solar images within the digital frames, along with the additional de-trending of low-frequency variations of the data obtained at Crimea and Mt. Wilson may improve the accuracy of the diagnostic diagrams computed from these data.

3. CALIBRATION AND UPGRADE OF INSTRUMENTS

It is interesting to note that some of the posters addressed the problems that are related to the calibration of the various helioseismic instruments and to obtaining an improved understanding of the characteristics of the signals which are being observed. In this way, Bogart et al., Evans et al., and Beck et al. reported on the status of the MDI instrument and on the modifications planned for improving the overall calibration of the MDI signal. Also, Pintar & Toussaint showed a simple and reliable method for reducing the noise which has been mapped into the GONG oscillation images during the GONG calibration runs. Pohl & Anderson described modifications of the GRASP software that generates rotationally-corrected (ℓ, ν) diagrams from the GONG observations. These changes were designed to upgrade these diagrams from serving solely as quality-assurance devices to full science-quality products. Continuing with GONG software and hardware developments, Harvey et al. described the high-resolution upgrade of the GONG instrumentation which will be made by replacing the existing small-format cameras with 1024 × 1024 pixel CCD cameras at the GONG sites.

On the other hand, Ulrich et al. showed several ways of calibrating the signals that can be derived from the GOLF monochromatic blue-wing observations. In this context, a stability study of the GOLF blue wing signal which extended through recent observations was reported by García et al.(paper 2). Pallé et al.(paper 2) presented similar work in which they discussed the nature of the GOLF one-wing observational mode and showed that not only GOLF but also other spectrometric techniques which calculate ratios (with either wing’s monochromatic measurements) do not yield pure velocity signals but instead also contain some contamination from intensity-like signals. Moreover, impressive work was reported by Henney et al. (papers 1 and 2) in which intercomparisons were made between calibrated data and power spectra from both the GOLF and MDI instruments. Finally, Chaplin et al. (paper 2) discussed the strategies of optimizing a multi-station helioseismic time series over a targeted frequency range and gave practical examples using BISON network data.

4. FITTING STRATEGIES

There is now an open debate going on concerning the convenience of fitting either the Fourier Transform or the power spectrum of an observed time series. This debate is occurring because, even though no posters were presented which compared all of the parameters which can be obtained from such fits, it seems clear that for at least some of the parameters (namely the splittings), there can be differences which seem to be systematic (Appourchaux, Rabello Soares et al.). Furthermore, it seems that there are no convincing arguments yet to indicate that one approach is significantly better than the other. A full comparative study of some observational data set, in which all of the fitting parameters as the splitting were calculated using both methods, would be very useful so that we can better assess the systematic differences.
Additional interesting points of discussion concern the choice of the model which is to be fit to the data and the details of how the selected model is to be determined. For instance, one key question is whether each single mode \((n, \ell, m)\) has to be fit or whether an approximation of the rotationally-induced frequency splitting of that multiplet (expressed in terms of Legendre polynomials or their equivalents) should be used to reduce the number of separate spectra which are to be fit. This is the issue of whether the individual zonal, tesseral, and sectoral spectra or the so-called “m-averaged” spectra should be employed. Moreover, a similar question should be asked in relation to the background (Hill et al.); it is well known that on top of the granulation background there is the contribution of the long tails of the Lorentzian profiles of the peaks which is quite significant in changing the frequency dependence of the background. Some of the authors believed that the background should be fit consistently for an entire one-dimensional p-mode spectrum in the case of the single-pixel instruments (Roca Cortés et al. [paper 1]) or in a kind of gigantic, collective, two-dimensional fit of modes and sidelobes for the spatially-resolved instruments (Meunier & Jefferies). These models were proposed to replace the existing multiplet-by-multiplet fits whose background results are often not consistent from peak to peak.

A comparison of these two strategies yields systematic variations in some oscillation parameters, mainly at frequencies higher than 3 mHz. Therefore, it appears as though such whole-spectrum fits may better define the true solar background and, furthermore, they may help to find the true shape of the peaks in the power spectrum. This point also relates to the question of fitting asymmetrical line profiles to the observed peaks rather than symmetrical ones; such asymmetry becomes better defined as the length of the frequency window that is used around each mode is increased. This is one more reason for employing larger intervals of frequency in the fits. The particular discussion on asymmetric profiles in the fitting models (Christensen Dalsgaard et al., Gavryusova & Gavryusyev, paper 1) was shifted to Working Group Session 6 in which these papers were presented orally.

5. RECENT RESULTS

5.1. Frequencies

Andersen et al. (paper 2) reported comparative studies of low-order (below 17) and low-degree solar p-modes in the VIRGO experiment data in which modes below 1.8 mHz are very difficult to detect; however, when using MDI velocity data and BISON data, modes could be detected as at frequencies as low as roughly 1 mHz. This topic also included the contribution by Schou in which he showed the difficulties of detecting these modes and questioned how low in frequency we will ever be able to go in detecting oscillation peaks; Schou even went so far as to place a ballot box on his poster in which he asked for suggestions. At the conclusion of the Workshop, Schou announced that the consensus opinion was 571 \(\mu\)Hz for the fundamental mode at \(\ell = 30\) and 694 \(\mu\)Hz for the \(p_1\) mode at \(\ell = 17\). Schou also reported receiving other, less serious ballots which we will not describe here.

This issue was also addressed in the poster by Régulo et al., who used the GOLF data base. Although the lowest well-measured frequency so far was \(\nu = 1236.62\) \(\mu\)Hz, it now appears that there may be a hope of identifying some lower-order modes in the future using the new analysis techniques described earlier in the session. (see section 2.). Also, using multivariate spectral analysis with VIRGO radiometric data, Finsterle & Fröhlich used data from the sunphotometer channels to remove correlated noise from the VIRGO Total Solar Irradiance (TSI) spectrum. After cleaning the TSI spectrum in this manner, they reported the identification of some additional low-order peaks, although only one of them (that of the \(\ell = 1\) and \(n = 1\) mode) was close to a frequency previously predicted by a solar model.

Appourchaux presented frequencies from the Luminosity Oscillations Imager (LOI) of the VIRGO experiment which he obtained from a two-year long time series which extended from March 1996 through March 1998.

Howe & Hill described how they have taken Hill et al.'s calculation of the GONG leakage matrix and have begun to use it in computing new estimates of the modal frequencies for the low-degree p-modes. Gavryusova & Gavryusyev (paper 2) employed the longest possible GONG data sets (of 830 days in duration) to look for low-degree frequencies corresponding to the minimum conditions of solar activity.

On the other hand, Bertello et al. (paper 1) conclude that no change in frequencies and splittings, within errors, is seen between the MDI and GOLF data. Similarly, results from multi-tapering analysis show that frequencies from GONG and from the MDI Medium-\(\ell\) program also agree to within 1\(\sigma\) (Komm et al., paper 1), differing only in the background slope at frequencies higher than 5 mHz. Furthermore, it is interesting to note that, when looking at the solar limb using MDI, as well as South Polar data, Toner & Jefferies were able to find similar frequencies in the two sets of spectra they computed from such “sector-annulus” observations. A final interesting result was reported by Garcia et al. (paper 1) on the appearance of an oscillatory signal beyond the acoustical cut-off frequency in the GOLF data, which consists of the so-called “pseudo-modes.”

Rhodes et al. described the only sets of high-degree p-mode frequencies to be presented at the SOHO6 Workshop. Specifically, they presented frequencies ranging up to \(\ell \approx 1000\) from the MDI Full-Disk Program and they compared many of these frequencies with a similar set of frequencies obtained at the same time from ground-based observations obtained at the Mt. Wilson Observatory (MWO).

Andreev and Kosovichev presented the results of some numerical simulations they conducted of atmospheric oscillations which yielded quasi-periodic shock waves.
5.2. Frequency splittings

A great deal of work has been devoted to extracting the amount of rotationally-induced frequency splitting that is observed in the oscillating modes. In contrast to some previous results where the only controversy appeared to concern the splittings of the low-degree ($\ell \leq 4$) p-modes, this meeting highlighted the difficulties of properly determining the splittings at all degree ranges. For example, while the splittings of the medium-degree modes might seem to be well-determined and nice solar differential rotation curves have been produced inward to $0.3 R_\odot$, the invited review talk by Howe pointed out that there are inconsistencies in the two-dimensional internal rotation profiles which result from the use of different “peak-bagging” techniques on the MDI Medium-$\ell$ data and there are similar differences in the internal rotation results that are obtained when the GONG and MDI Medium-$\ell$ splittings are inverted and the resulting profiles are compared.

This Working Group Session also highlighted the problems associated with both the measurements of the low-degree and high-degree ($\ell \geq 140$) splittings. The principal reasons for the difficulties in determining the low-degree splittings are: 1) there are fewer components of each low-degree multiplet than there are for the larger degrees, 2) the maximum frequency splittings between the zonal and sectoral modes are therefore much smaller for the low-degree cases than they are for the medium- and high-degree cases, and 3) for the spatially-unresolved instruments such as GOLF, VIRGO, BISON, and IRIS, the peaks of several different degrees are crowded close together in the spectra, therefore yielding a worse determination of the splittings.

Moreover, the degree of power leakage has to be carefully taken into account when fits are made, especially on the $\ell = 1$ modes. Therefore, it was not surprising that many of the excellent works presented were efforts to determine such low-degree splittings and their uncertainties. Grouped by the source of the data which was used, these low-degree posters included those of: Rabello Soares & Appourchaux; Gavryusova, Gavryusov, and Di Mauro; and Howe & Hill, who employed GONG observations; Toutain & Kosovichev, who used MDI data; Appourchaux, who used LOI observations; Lazrek et al. and Fiery Frailon et al. (paper 1), who used GOLF data; and Chaplin et al. (paper 1), who employed artificial p-mode data in order to elucidate some of the difficulties in extracting the splittings from full-disc, low-$\ell$ data.

A summary of the status of these low-degree results was as follows: for modes with $\ell \geq 2$ all of the results that were presented agreed to within the quoted error bars; however for the $\ell = 1$ modes there seemed to be a difference which was slightly higher than 2$\sigma$ and which might possibly be significant. These two sets of $\ell = 1$ measurements were centered near 433 and 456 nHz, with the quoted error of each set being around 10 nHz. The 433 nHz result was obtained when the splittings were calculated from one of the data sets which has spatial resolution, while the 456 nHz value was obtained when disk-integrated data was used instead. Some possible explanations were put forward for this slight disagreement: a) for the GONG, MDI and LOI data an analysis of the leakage matrix was included and the Fourier transform was fit, although this method was shown to possibly underestimate the splittings in comparison to the results obtained from fits to the Fourier power spectrum for modes with $n \geq 18$; b) in the integrated-disk data (i.e., the so-called MDI LOI Proxy data, the LOI data, and the GOLF data) the fitting methods seem to behave such that when the linewidth increases the measured splittings also tend to increase, specially for modes with $n \geq 20$. Such a result was also found for the simulated data.

Therefore, a closer look at the systematic effects in these measurements is necessary in order to resolve the differences. One thing that can be ruled out is that fits using asymmetrical profiles do not seem to affect the splitting measurements. Nevertheless, we may also think that 2n is not a too big difference, but the effect of this difference is very important in the data inversion techniques applied to unveil the rotation rate in the core (Corbard et al., Eff-Darwich & Korzennik). However, the prospects for this topic look good as the statistical errors should decrease with time, provided the splittings themselves do not change with the solar cycle and provided the systematic differences can be eventually understood.

Switching to the high-degree p-modes, Rhodes et al. presented the first such rotational splittings to be obtained from the MDI Full-Disk data and they also compared these splittings with simultaneous splittings obtained from ground-based observations obtained at MWO. By comparing both the MDI and MWO high-degree splittings with the MDI Medium-$\ell$ splittings and with older observations of the photospheric rotation rate, Rhodes et al. demonstrated that all high-degree splittings are systematically affected by the blending-together of the p-mode peaks into ridges of power which occurs for all degrees above $\ell = 140$. They also demonstrated that great care will have to be given to the question of how the corrections to some previous results are to be computed in order to remove such systematic deviations from the surface rotation rate. Finally, Rhodes et al. also pointed out that such corrections will be essential before these splittings will be useful in inversions of the sub-photospheric solar velocity field.

5.3. Linewidths and energies

Work on these parameters indicates that the relative power of different multiplet components is very different for different n value multiplets of a given degree and is also different from the theoretically-computed average behaviour (Gavryusova & Gavryusov (paper 2), Rocca Cortes et al., paper 2). Therefore, fits with a fixed ratio of the power for the different n-values of the multiplets of a given degree could have an influence on the other parameters being fitted to such multiplets (Rocca Cortes et al., paper 2). Linewidths were also reported from the LOI data set by Appourchaux.

A more complete discussion of these interesting parameters and some of the other posters with work on this topic (i.e., those by Fiery Frailon et al. (paper 2), Rocca Cortes et al. (paper 2), Bertello et al. (paper 2), and Gavryusova & Gavryusov, paper 2) were
also shifted into Working Group Session 6, where the rate at which energy is poured into the oscillating p-modes was also discussed.

5.4. The 160-minute oscillation

Two studies tackled the question of looking for the 160-min solar oscillation in SOHO data. Scherrer looked at low- and medium-resolution MDI data to search for the amplitude and frequency of the power spectral peak which has been seen in several data sets in the past at a frequency corresponding to a period of almost exactly 160 minutes (Kotov et al., 1998, and references therein). Scherrer’s principal result was that the upper limit which he obtained from this MDI data was well below the power level seen in any of the earlier ground-based observations. Pallé et al. (paper 3) also reported a negative result based on GOLF data of up to 1st March 1998; in fact, these authors concluded that no coherent (in amplitude and phase) wave at the periods reported in the past exists above 1 cm/s. Therefore, unless such a signal has strong temporal variations in its amplitude, the obvious conclusion these authors reached was that the claimed peak is most likely an artifact due to the effects of the Earth’s atmosphere on the earlier, ground-based observations.

5.5. Intensity measurements

Interesting work relating to the properties of the solar background noise observed in VIRGO experiment (radiance and irradiance measurements) was reported by Andersen et al. (paper 1), who found no rotational modulation in the background noise signal. Certainly, the knowledge of this background is necessary for the search for solar g-modes. Such analysis at all frequencies (including those where the increasing magnetic activity shows its influence) was performed using multivariate spectral analysis techniques on photometric data from the SunPhotometer (SPM) devices on VIRGO by Anklin et al. Next, Jiménez et al. (paper 2) described their continuing search for gravity modes using the VIRGO data.

Completing this group of result presentations, Jiménez et al. (paper 1) reported phase and gain relationships between the intensity and velocity signals using data from the VIRGO and GOLF experiments which virtually confirmed earlier results. Furthermore, they also presented a new result which showed that these phase differences also depend upon the \( \ell \) value of the modes. Masillo & Marmolino presented an up-to-date review of such observed phase differences as functions of frequency, degree and height in the solar atmosphere in which they identified the additional work that is needed in future observational studies. They also noted that the comparison of such observations with theoretical predictions is a field that is still in its infancy.

6. PROGRESS REPORTS

In this section we heard about the progress towards an IRIS++ database which is to be open to the helio-seismic community and in which data from several different ground-based instruments (IRIS network, the Mark-I instrument of the BiSON station at Obs. del Teide, the MOF filter run at JPL, and the LOWL instrument) will be incorporated (Gelly et al.). A report on the results and highlights of the initial two years of the SOI/MDI Structure Program was also presented by Bush et al.. We also heard a report on the availability of the VAMOS data analysis pipeline (written in IDL) for the MOF instrument, a “Cacciani” type device, being operated at Napoli since February 1997 designed by Oliviero et al. Finally, we heard about a new ground-based network called RODOMA (for the ROme network for DOppler and MAgnetic oscillations) from Cacciani et al..

7. UNPRESENTED POSTER PAPERS

A few authors submitted abstracts of poster papers which were placed into Working Group Session 1, but were unable to attend the Session to present their results. These authors included: Z. Benkhaldoun, S. M. Chitre, R. Kariyappa, and W. Ni.

ACKNOWLEDGMENTS

We wish to acknowledge the organizers of Working Group Session 6 for nicely accepting the transfer of some of our scheduled posters to their session. We also thank the SOC for relying upon us for the organization of Working Group Session 1 and for the preparation of this report. We also wish to beg the pardon of all of our colleagues whose poster presentations have either been: 1) mistakenly omitted from this report or 2) mis-interpreted. None of the speakers is responsible for any false impressions which we may have given here about their work. We also apologize to all of the attendees of Working Group Session 1 who made cogent comments from the floor but whose comments are not cited here. Finally, we wish to point out that this report would have been even more elaborate if the World Cup tournament had not taken place during 1998, even though neither of the authors’ national teams survived very long in the competition. We offer our congratulations to our French colleagues on their World Cup Championship.

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Session II

Seismology of Sun-like Stars: Techniques and Strategies