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Results from the LOWL instrument

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Abstract. We present various results from one year of observations with the LOWL instrument, which is designed to observe oscillations with degrees l from 0 to about 100. Among the results shown is an inversion for the solar rotation rate down to approximately $0.2R_\odot$, Given the long duration of the observations we have been able to obtain very low errors and good radial and latitude resolution in a substantial part of the solar interior.
We will also present results of analyzing different parts of the time-series to look for temporal variations in mode frequencies and show that they seem to be associated with variations in solar activity.

Key words: sun:rotation, activity, inversions

1. Introduction

Inversions of intermediate-degree frequency splittings (Duvall, Harvey and Pomerantz, 1986; Christensen-Dalsgaard and Schou, 1988; Brown *et al.*, 1989; Rhodes *et al.*, 1990) indicate that throughout the convection zone the solar angular velocity follows a surface-like latitude distribution with a transition to latitude independent rotation near the base of the convective envelope. Below $\sim 0.4R_\odot$, however, the solar rotation rate has been highly uncertain due to a lack of accurately measured low degree splittings. Attempts to measure these splittings using spatially resolved observations have generally failed due to instrumental noise. Integrated light observations have shown the stability to observe low-degree oscillations. However, these observations are unable to discriminate spatially between individual oscillation modes, and thus require modeling of the blended modes to obtain the splittings. LOWL combines the required stability with spatial resolution.

2. Observations

The observations used in this study were obtained with the LOWL instrument (see Tomczyk *et al.*, 1995b), which is a velocity imaging instrument based on a Potassium Magneto-Optical-Filter (MOF), thereby making it stable. Full disk images are obtained every 15 seconds, but images were averaged over 1 minute intervals for the present study. The instrument is located on Mauna Loa on the island of Hawaii. The observations used here were collected over a 1 year period from the beginning of operations on Feb 26, 1994 to Feb 25, 1995. The duty cycle is $\approx$20% and the frequency resolution $\approx 0.032\mu Hz$.

3. Results/discussion

The method by which mode parameters are obtained from the velocity images is described in Tomczyk *et al.* (1995a). The variation of mode frequency ω_{nlm} with azimuthal order m was expanded using so-called a coefficients (Schou *et al.*, 1994). The resulting dataset shown in Fig. 1 is comprised of 3398 a_1, a_3 and a_5 coefficients for 1154 (n, l) multiplets with l ranging from 0 to 99. Modes were found down to $1062\mu Hz$ for $l = 45$, $n = 1$.

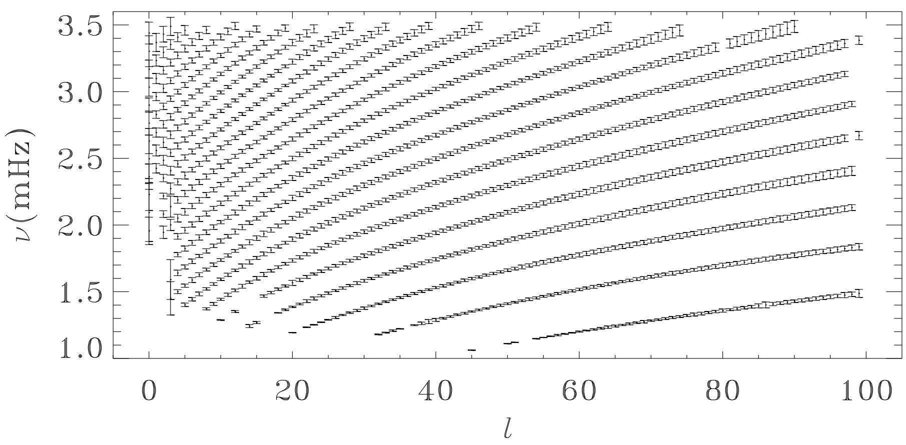

Figure 1: $l - \nu$ diagram showing the modes used with 1000σ errorbars.

The odd a coefficients are related to the rotation rate by integral equations (Schou *et al.*, 1994). To infer the rotation rate we have employed a 2-D Regularized Least Squares (RLS) inversion method, as described in Schou *et al.* (1994) with $\mu_r = 10^{-7}$, $\mu_\theta = 10^{-3}$. Results of such an inversion have been shown in Fig 2. The resolution in the latitude direction could be improved considerably in the outer parts of the Sun if one were to have more a coefficients per multiplet; with $a_1 - a_5$ there is no possibility of significantly improving the latitudinal resolution.

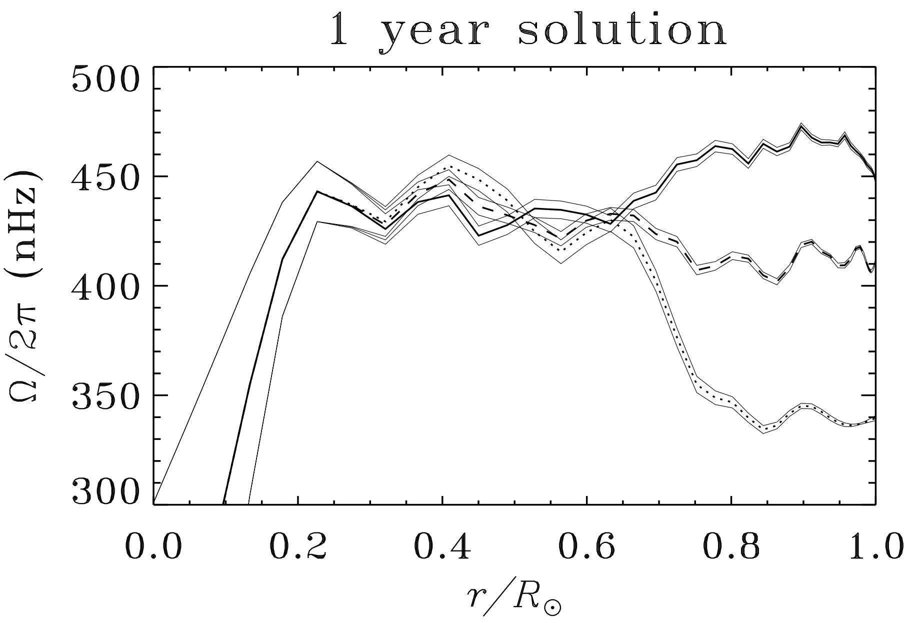

Figure 2: The inferred rotation rate at the equator (solid line), at colatitude 45° (dashed line) and at the pole (dotted line). 1σ errors are indicated by the thin solid lines.

The errors shown in Fig. 2 are estimates of the random error as propagated from the input splittings. The difference between the inferred and the true rotation rate could be much larger due to unresolved features in the true rotation rate. At the bottom of the convection zone we see a transition from surface-like differential rotation to a rotation rate that is independent of latitude, in basic agreement with previous findings (Christensen-Dalsgaard and Schou, 1988; Brown *et al.*, 1989). To within the resolution of our inversion, the differential rotation vanishes at a point near the base of the convection zone. In the convection zone a number of apparently statistically significant oscillations occur. Given the low duty cycle of the LOWL instrument there is a significant risk of problems with temporal sidelobes of modes with $l \pm 1$ in the region where $\mathrm{d}\nu/\mathrm{d}l \approx (1\mathrm{day})^{-1} \approx 11.57\mu Hz$ corresponding to modes with a radial turning point of $\approx 0.85R_\odot$. While we do not believe that temporal sidelobes are a problem, one should be cautious drawing conclusions before the problem has been investigated further.

Below $r \approx 0.65R_\odot$ we find no significant variation of the rotation rate. Statistical uncertainties in the current data prevent the reliable estimation of the rotation rate below $r \approx 0.2R_\odot$, the significance of the difference between the rotation rate at the center of the Sun and at $0.2R_\odot$ is only about 2σ. However it is interesting that a similar drop has recently been reported by the BISON group (Elsworth, *et al.*, 1995).

In $r \lesssim 0.3R_\odot$ we see no variation with latitude. This is simply a reflection of the fact that below this depth we cannot localize kernels at different latitudes and is a fundamental limitation imposed by the fact that the deepest interior is only sampled by low-degree p-modes, for which there are few different m values. On the other hand, further out (e.g. at $r_0 = 0.5R_\odot$) we can achieve some latitudinal resolution. If there were substantial latitudinal variation at $r_0 = 0.5R_\odot$ we should be able to detect it.

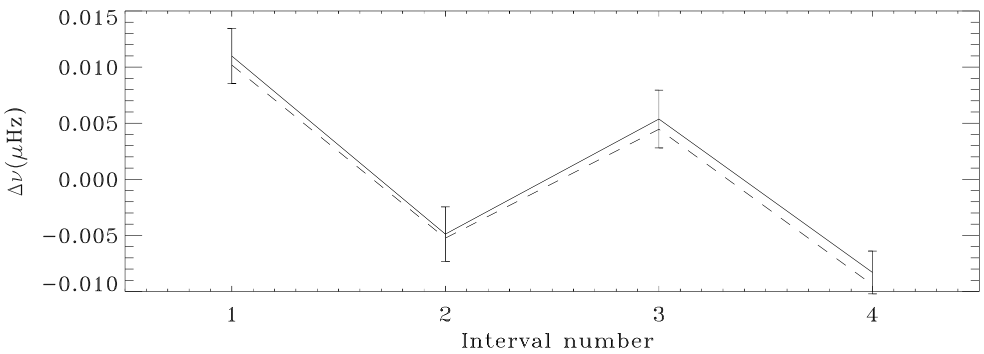

Figure 3: Averaged frequency differences as a function of time for the modes with $20 \leq l \leq 60$ and $2600\mu Hz \leq \nu \leq 3200\mu Hz$. The dashed line shows 0.0052 times the 10.7cm flux in units of $10^{-22}Wm^2Hz^{-1}$, minus the average over the year.

To investigate possible temporal frequency changes we have divided the 1 year dataset into four 91 day subsets. Only modes common to the four intervals have been used and modes with extreme values in one or more intervals were excluded. Fig. 3 shows the differences between the frequencies determined in each time period and those from the full 12 months. As can be seen the changes correlate extremely well with the activity, however the constant of proportionality is twice that reported by Bachmann and Brown (1993), despite the use of the same modes. The cause of this discrepancy should clearly be investigated further. Among the problems are that we used longer time intervals than they did and that we only have numbers close to solar minimum. However the clear signal would seem to indicate that we can subdivide the time interval further.

After we have finished the analysis of this 12 month dataset we expect to publish the mode parameters and make them publicly available. We will attempt to fit more a-coefficients and shorter time-strings. LOWL is still collecting data and we currently have over 20 months data. When we have acquired 24 months we will analyse the resulting time-series.

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