ON THE SOLAR CORE ROTATION – IRIS RESULTS

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ABSTRACT The best time series of velocity residuals obtained by the IRIS network so far has been analyzed with the specific aim of optimizing the signal to noise ratio in the low order p-mode frequency range, around 2 mHz. It resulted in a very significant improvement of this signal to noise parameter, making possible the detection of individual modes with amplitudes as low as 3 mm/s. With such a low noise level, the number of detectable peaks with a linewidth narrow enough to make the rotational splitting clearly resolved has been dramatically increased. Six modes of degree l= 1, five of degree 2 and again six of degree 3 have been used for splitting measurements. For l=3, 2 and 1 respectively and within their error bars, the splittings appear to be slightly larger than the surface value, and very possibly increasing with decreasing degree. Assuming a known rotation in the solar envelope and using the rotational kernel properties for l=1, 2, 3 and the three measured values, we derive some crude estimation of the behavior of the rotation in the core and investigate a simplified model of core rotation described by two parameters. The significance of these results is briefly discussed.
INTRODUCTION

The estimation of the solar core rotation requires an accurate measurement of the splitting of the lowest degree modes, which is a very difficult task for any imaging measurement. The relatively large values of the sidereal splitting which had been initially reported about 10 years ago seem now to be excluded by the most recent results, based on much longer data sets (Toutain and Fröhlich 1992; Loudaghis et al 1993; Toutain and Kosovichev 1994). The new values have been obtained by the full disk instruments, which give access to the modes of degree l=0 to 3. This measurement has to face the well known difficulties: in the five-minute range where the signal to noise ratio is high, the linewidth of individual peaks is not narrower than the distance between the split components, producing interferences which are dramatically damaging the precision. In the very low p-mode frequency (2 mHz or less) range, the peaks are narrow enough to be clearly resolved, but they have a poorer signal to noise ratio, and only an extremely long time of integration, by the virtue of the statistics, will finally provide accurate number.

It must be kept in mind that the contribution of the solar core itself to the splitting of these modes is very small (a few percent). A consequence is that an uncertainty of a few percent on the numerical value of the splitting with not permit to distinguish a solar core rotating at the surface rate from another one twice faster. Again, it must be kept in mind that a few percent of the splitting is of the order of 15 mHz, or in other words 1/(2 years)! It cannot be expected, then, to reach this accuracy on the splitting of individual modes with data sets of a few months.

As was pointed out recently by Toutain and Kosovichev, 'it is reasonable to assume that the frequency splittings can be approximated by a unique value for all the observed low-degree modes, and therefore can be estimated more reliably from the existing data because of the effective averaging'. They mean all modes of degree 1 and 2, which are accessible in the IPhIR data. This assumption is based on the fact that for a not very fast rotating core, the low degree mode splittings are, at most, only a few percent different from the mean rotation frequency of the rest of the solar model, and the individual differences between them would be only a fraction of these few percent, presumably well within the error bars.

DATA AND ANALYSIS

We present here a still preliminary analysis of an IRIS network data set, which provides the splitting for the l=1 and 2 modes, and also for a few modes of degree l=3.

The data was obtained in 1991 by the four IRIS stations of Kumbel (Uzbekistan), Oukaimeden (Morocco), Izana (Tenerife, Spain) and La Silla (Chile). It covers 115 days, from July 1st to October 23rd, with a duty cycle slightly less than 60 percent.

The power spectrum was computed with the deconvolution of the window function, using both the simple method of autocorrelation division (Fossat 1992; Lazrek and Hill 1993) and the Richardson-Lucy algorithm (Pantel and Fossat, these proceedings). Both simple (1-0) and weighted (see Fossat 1992) window functions have been used for these deconvolutions. The last one provides a better performance in term of the signal to noise ratio in the low frequency range (where
Fig. 1. The six modes of degree $l=1$, as they have been used in relative position and scale for averaging.

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Fig. 2. Same as Fig. 1 for five modes of degree $l=2$. 
Fig. 3. Same as Fig. 1 for six modes of degree $l=3$
the signal is weak), while the first one is more efficient for reducing the sidelobes contribution (more important in the five-minute range where the signal to noise ratio is high in any case).

We relax a little the here above mentioned assumption of an almost constant value of the splitting of all accessible modes, and we only assume that it is true for a given degree. Then, separately for \( l=1, 2, \) and 3 it is attempted to average the peaks of all modes below a given radial order (chosen as the last one which shows a splitting visible by eye). The fit of a pair, a triplet or a quadruplet of Lorentz functions is then made on the averaged peak. The advantages of this procedure are:

- Only one fit is made, reducing the number of parameters to be computed by the program and thus increasing the quality of the fitting procedure;

- After averaging several peaks together, the distribution of points around the Lorentz shape can be assumed to be normal, thus permitting the use of a standard least square fit (this point is important because after deconvolution, this distribution is neither normal nor following the \( \chi^2 \) -square law).

The drawback is the unavoidable uncertainty in the respective positions of the individual peaks to be averaged, this resulting essentially in a broadening of the Lorentz function to be fitted and making it slightly different from the true Lorentzian shape.

The same procedure has been applied to a series of radial mode peaks \( (l=0) \), just to check that no splitting is measured in this case.

The first three figures show, for each degree respectively, all individual peaks which have been used for this averaging. Figure 4 shows their weighted average. Each peak has been weighted according to its approximate integral (approximate because in the case of the lowest frequencies, the signal to noise is not very high), so that they all provide comparable contribution to the mean doublet or multiplet profile. A double, triple or quadruple Lorentz profile has been fitted on each average, with the following constraints:

- the triplet and quadruplet are forced to be uniformly spaced
- the linewidth is taken as only one free parameter, forced to be the same for all the components of a multiplet.

ATTEMPT OF INTERPRETATION REGARDING THE CORE ROTATION

As was done previously in Loudagh et al (1993) with only the splitting of \( l=1 \), the core rotation is estimated by means of the following assumption: the rotation is supposed to be known outside the core, from the imaged splitting inversions. Three theoretical splittings are computed using the corresponding rotational kernels, averaged for each degree, over the set of measured modes. The core rotation is then computed by least square fitting these splittings on the measured values.

First one unique mean value has been estimated for a core radius \( r/R \) of respectively 0.2, 0.3 and 0.4, the rotation being assumed uniform inside this core. The figure 5 shows these three values. The measured values of the splitting of \( l=1 \) and 2 being significantly (although slightly) larger than the mean value of the rest of the model, the core rotation is found faster and increasing with a decreasing core radius. The error bars displayed at both ends are the observational errors just propagated through the least square fit. The other bar in the center is produced by a change of 2 percent of the assumed known
Fig. 4. For each degree, the average of individual multiplets is shown (continuous line) with the fit of a Lorentzian multiplet (dashed line). The individual Lorentz profiles are shown in dotted line (Horizontal scale, 1 point = 0.127 μHz).
rotation rate outside the core (an increase by 2 percent outside producing the
slowest rotating core, of course).

Then, an attempt is also made to model a two-level rotation rate inside
the core. Having measured three values could, in principle, make possible to
try a three-level model, but the error bars, though small, are still too large to
make this attempt realistically useful. The figure 6 shows the resulting rotation
profiles assumed constant respectively on $r/R=(0 - 0.2)$ and $(0.2 - 0.3)$ and on
$r/R=(0 - 0.2)$ and $(0.2 - 0.4)$. The error bars have the same meaning.

**DISCUSSION**

The error bars on the observational results have been estimated by means
of the statistical behaviour of individual peaks produced by a damped and
randomly excited randomly oscillator (Woodard 1984, Duvall 1988) taking into
account the signal to noise ratio (Toutain and Appourchaux 1994) and the five
or six-peak averaging.

Within this statistical uncertainty, it seems highly probable (Fig. 5 and 6)
that the solar core is rotating a little bit faster than the envelope. However, this
conclusion must be regarded as still preliminary and subject to further revision.

Indeed, if one look at the individual splittings, mode by mode, on the first
three figures (the individual splittings have not been calculated, but they are
roughly directly visible on the plots), their dispersion appears to be larger than
what the statistics predicts. Four reasons can be invoked to have in fact a slightly
larger level of uncertainty, with an amount difficult to estimate:

- The power spectra have been obtained through a deconvolution procedure.
  It has been checked on many simulations that it does not significantly affect
  the line shape. However, in the case of the $l=2$ modes, the increased dispersion
  of the noise distribution at the former location of the suppressed sidelobe of $l=0$
does increase the uncertainty a little bit.

- The average of several multiplets contains the uncertainty on their relative
  positions, this changing slightly the shape of the lorentz function which is then
  imperfectly used in the fit.

- The fit is made by the least square Marquard method. This is adequate
  because of the averaging, but it has been checked on simulations that it is slightly
  less precise than the ideal maximum likelihood fit in the ideal situation of a $\chi$
  -square distribution.

- It must be finally noted that although narrow in this frequency range,
  the individual peaks still have a linewidth of the order of 0.5 $\mu$Hz, and there
  is still some interference in the overlapping wings of the multiplet peaks. This
  interference increases the uncertainty, as does the relatively poor signal to noise
  ratio.

A further analysis will take more individual peaks into account, and also
will use more (already existing) IRIS data. The decrease of the observational
error bar, if the analysis is made carefully, is now only a question of time. At
first order with several projects providing full disk data, it can be said that this
error bar will decrease, from now on, as the square root of the time. To-day, we
can only recommend the theorists playing the game of inversion to use as much
available data as possible, from as many instruments and as many authors as
possible, to improve this statistical uncertainty.
Fig. 5. Estimation of a constant rate of rotation $\Omega$ (in $\mu$Hz) in a core of radius $r/R = 0.2$, 0.3 or 0.4, obtained by fitting the averaged theoretical splittings on the measured values, and assuming a known rotation in the envelope (dashed line). See text for more detail.

Fig. 6. Estimation of the core rotation $\Omega$: the core is now separated in two regions, the first one till $r/R=0.2$ and the second one respectively till $r/R=0.3$ (full line) or 0.4 (dotted line).
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REFERENCES

Pantel A., Fossat E. 1994, these proceedings.