Meridional Circulation from Large Aperture Ring Diagrams

I. González Hernández[1], R. Komm[1], T. Corbard[2], F. Hill[1], R. Howe[1]

[1]NSO, Tucson, AZ, [2]Obs. de la Côte d'Azur, Nice, France

Introduction

Ring Diagram analysis, a local helioseismology technique, has proven very useful in order to study the solar subsurface velocity flows down to a depth of about $0.97R_o$. The depth range is determined by the modes recovered in this type of analysis and thus depends on the size of the analyzed area. Extending the working area allows us to detect lower *l* modes that penetrate deeper in the Sun. However, there is a compromise between the size of the patch and the validity of the plane wave approximation used by the technique. In this work we present a preliminary attempt to go deeper under the solar surface using Ring Diagrams. Meridional flows are derived by using this technique.

Data Analysis

We have applied Ring Diagram analysis to patches of 30º diameter over the solar surface as they crossed the solar central meridian. These patches are twice the size of the typically studied sections of 15º in diameter. A set of 15 overlapping sections centered at latitudes 0º, ±7.5º, ±15º, ±22.5º, ±30.0º, ±37.5º, ±45.0º and ±52.5º have been analyzed for 25 intervals of 1664 minutes during Carrington rotation 1989.

Figure 1 shows a comparison between the set of modes in the range *l*=0-600 fitted using a 15º patch and the ones fitted when using a 30º patch. Modes in the *l* range of 100 to 200 are recovered with the larger areas. We are particularly interested in these low *l* modes for this study.

L-curves plots showing the trade-off between resolution and formal errors obtained using an OLA inversion for a 15º patch and for a 30º one are shown in *figure 2.* In both cases the patch was centered around the solar equator. The different solid lines (or L-curves) correspond to different depths as shown on the plot. Points obtained using the same regularization parameter are linked by a dotted line. An optimal choice of the regularization is located at the corner of the L-curve for each depth (red dotted line). It can be seen from the graphics that using 30º patches allow us to reach a better compromise resolution/error at depth below 10 Mm.

Figures 3 presents the inverted azimuthal velocities for a 30º patch centered at the equator using OLA and RLS. The horizontal bars represent the width of the averaging kernels. The vertical bars are the formal 1-σ error bars. The corresponding averaging kernels for the chosen regularization parameter are also shown. The differences in the kernels explain, at least partially, the differences between the two solutions.

For this particular work we have used an RLS inversion although more work needs to be done in order to find the optimal regularization parameter as a function of depth and the best inversion method for this task.

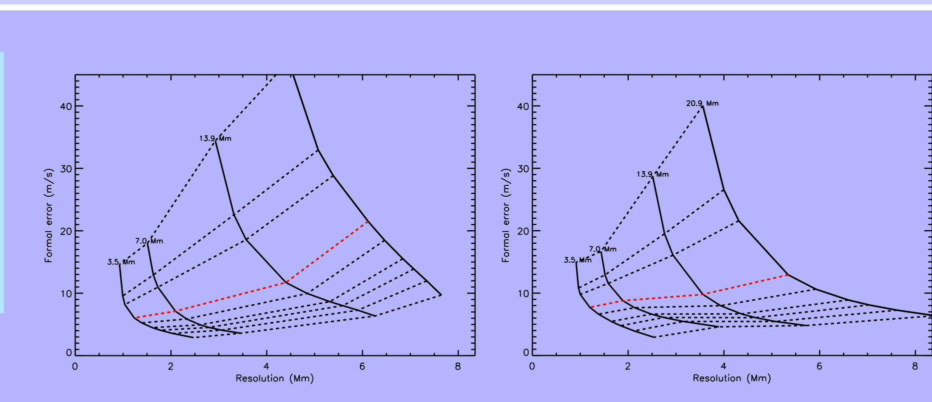

Fig 2: *L-curves* Trade-off between resolution and formal errors obtained using an OLA method for a 15º patch (left) and for a 30º patch (right)

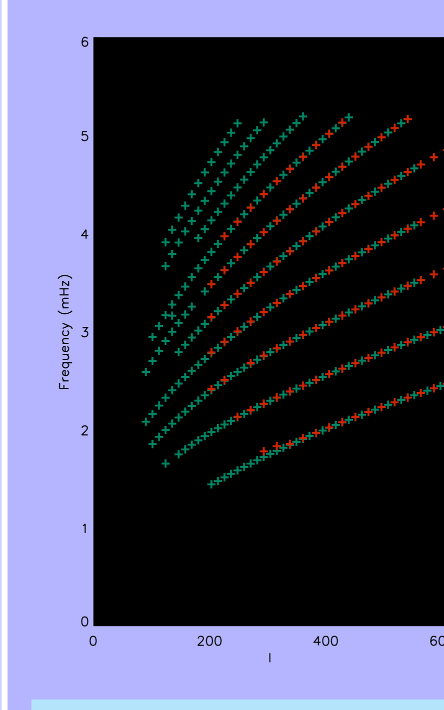

Fig 1: Comparison between fitted modes using a 15º diameter region (red) and a 30º one (blue)

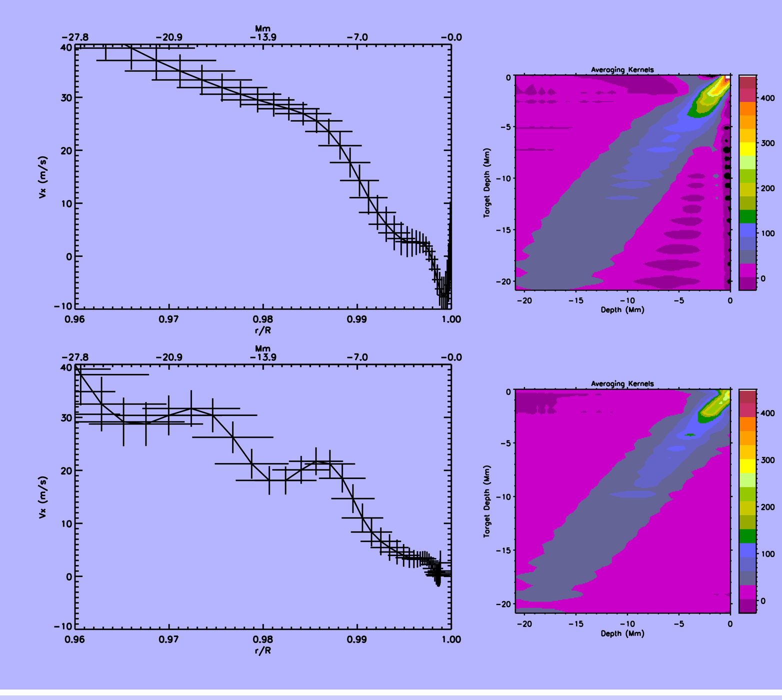

Fig 3: Horizontal velocities for a 30º patch centered at the equator using RLS (top) and OLA (bottom). The right hand panels show the kernels for the chosen regularization parameter. The RLS kernels appear to be more peaked than the OLA kernels near the surface and wider below 10Mm.

Results

The meridional component of the horizontal flows is presented in *figure 4*. A systematic displacement between GONG and MDI results can be observed. Below 0.97 R_o, MDI shows a strong equatorward flow at high latitudes that has been named the *countercell* in previous works.

In order to validate the horizontal flows obtained, we compare the differential rotation obtained by averaging the zonal component of the horizontal velocity vectors for the whole CR 1989 with the global one obtained for a 3 month series around the same period. We have added back to our local results the rotation tracking rate. *Figure 5* shows the comparison between the rotation rate obtained using local analysis with both 15º patches and 30º patches. It can be seen that the larger aperture rings provide a more accurate measurement of the rotation rate for deeper layers. The continuous increase of the rotation below a certain depth is probably due to the inversion technique. We also find a systematic displacement between GONG and MDI rotation rate (not seen in global analysis) that is still under investigation.

Finally, we calculate the divergence of the measured horizontal flow components. Using the continuity equation, we derive the vertical velocity component from the measured divergence of the meridional horizontal component. *Figure 6* shows the vectors resulting from combining the meridional component of the averaged horizontal velocity flows with the calculated vertical component for both GONG (top) and MDI (bottom). While the *countercell* was not easily visible for the GONG data when plotting only the meridional component, here a strong down flow can be seen in the same region where MDI shows the *countercell*.

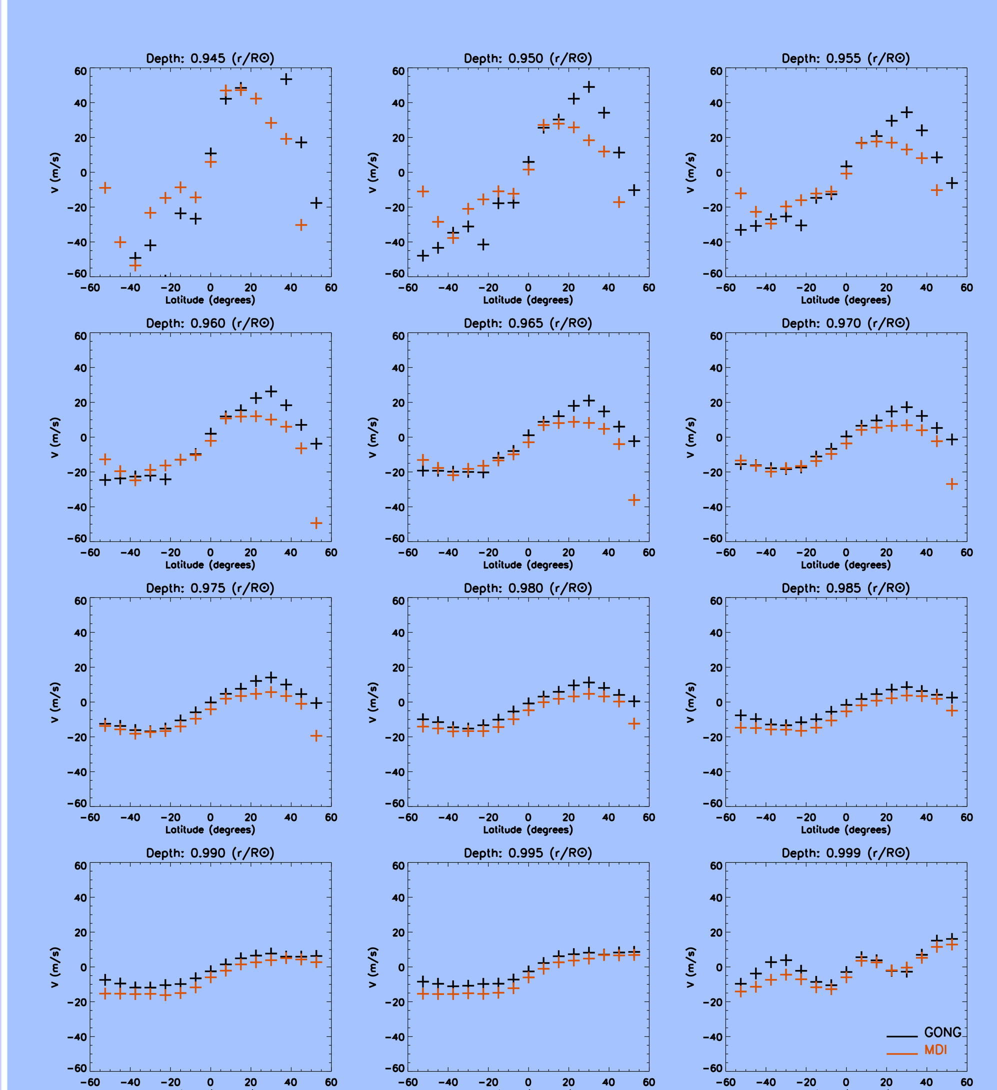

Fig 4: Meridional flows obtained from Ring Diagram analysis for GONG (black) and MDI (red) for different depths as an average of 25 consecutive series of 1664 min taken during CR 1989

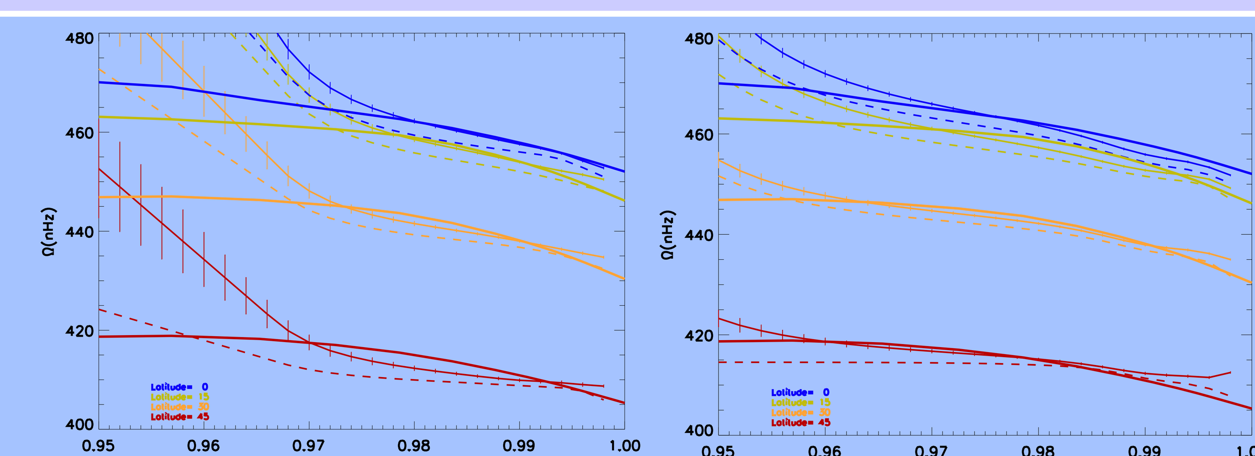

Fig 5: Rotation rate for several latitudes, 0, 15, 30 and 45 from Global Analysis (thick solid line) and from Ring Diagrams (GONG solid line, MDI dashed line). The left panel shows the results obtained using the typical 15º patches, the right panel the same results using the larger 30º patches.

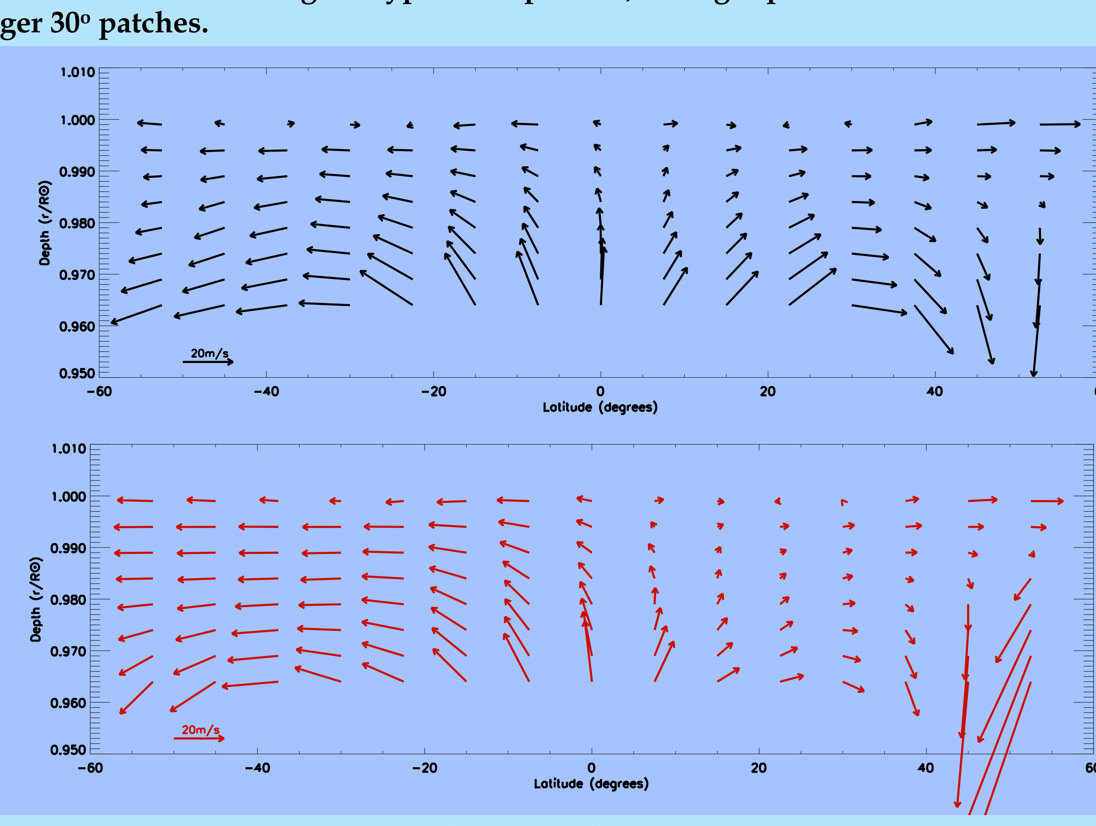

Fig 6: Meridional circulation as a function of depth obtained by combining the U_y component of the horizontal velocity flows from Ring Diagrams and the calculated vertical component for GONG (top) and MDI (bottom)

Conclusions

- We have shown that large aperture ring diagrams are highly effective in order to search for differential rotation and meridional circulation in deeper layers under the solar surface.
- The inversion method and the optimal regularization parameter for this type of work are still to be determined.
- The presence of the countercell/down flow and the systematic differences in the averaged horizontal flows between GONG and MDI are still under investigation. We suspect geometric and/or calibration issues with the instruments that affect local analysis but do not affect global results.
- Our intention is to use GONG continuous velocity data to search for a meridional circulation variation with the solar cycle. A previous study by Chou *et al.* using TON data found variations that were different for the declining phase and the rising phase of Cycle 22. It must be noticed that they also find a general increase with depth in the meridional flows of up to 40m/s. Our work agrees with a slight increase in the magnitude of the meridional flows with depth; however, the major increase below 0.965 R_o is suspected to be an artifact of the inversions, and is under investigation.

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