Subsurface flows from ring diagram analysis

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Abstract.
Since it was introduced, almost 20 years ago, ring-diagram analysis, a local helioseismology technique, has provided a variety of results, from large-scale motions on the Sun, such as differential rotation and meridional circulation, to the more localized studies of flows associated to active regions and filaments. This paper presents some relevant results obtained by several authors using this method that help to constrain the solar dynamo models, as well as a discussion of the outstanding issues and areas for future improvement.

1. Introduction
Large-scale flows play an important role in solar dynamo theories. Hence, properly describing the material motions at the surface and subsurface layers has become an important goal of helioseismology research. One of the major contributions of global helioseismology has been the inference of the Sun’s differential rotation throughout the convection zone and deeper radiative interior. However, global analysis is insensitive to asymmetries between both hemispheres, meridional circulation or localized flows such as those surrounding magnetic areas. To research these aspects it is necessary to use local helioseismology techniques such as the ring-diagram analysis [1].

Since its first application to obtain a 9-patch velocity solar subsurface flow map [2], ring-diagram analysis has yielded novel and exciting results. Nowadays, the standard technique obtains a horizontal velocity vector at different depths for a circular area with a diameter of 15° [3]. In practice, a mosaic of 189 separate ring-diagram analyses filling the solar disk out to ~60° from disk center with overlapping analysis regions and centers separated by 7°.5 in latitude and longitude is constructed. However, smaller and larger areas and final maps have also been used for particular studies.

This paper reviews some of the major contributions to the research of solar subsurface flows obtained by using the ring-diagram analysis technique.

2. Differential Rotation
Global helioseismology has successfully mapped the Sun’s differential rotation throughout the convection zone and deeper radiative interior [4]. The results from global helioseismology are typically shown at different latitudes as an average of what is happening in both solar hemispheres. Figure 1 shows a comparison between the differential rotation rate obtained by averaging the zonal component of the horizontal velocity vectors for Carrington rotation 1989 with the global one obtained for a 3 month series surrounding that Carrington rotation[5]. Results using both 15° and 30° areas are shown. It can be seen that the larger-aperture rings
provide a more accurate measurement of the rotation rate for deeper layers. There is a clear improvement in the results from local analysis when the larger areas are used, however, a loss of spatial resolution is involved when using such large areas.

Another subject of research of ring analysis is the so-called “torsional oscillation”, weak bands of faster and slower than average rotation that are interpreted as zonal flows. Howe et al. (2006) [6] compared the torsional oscillation obtained from local analysis with that from global analysis. Figure 3 shows the results obtained from global helioseismology and ring diagrams. Although the trend of the bands moving toward the equator can be seen in both plots, because of the gaps in the high resolution data available to perform local analysis, the results from local helioseismology are very sparse.

Global analysis does not have the capability to distinguish between hemispheres. For that, a local helioseismology technique needs to be used. Figure 2 shows the temporal variation of the separated North and South hemisphere flows at different latitudes and depth obtained by applying ring diagrams to approximately three years of Global Oscillation Network Group (GONG) data. Zaatri et al. (2006) [7] finds that for the period of time analysed, the zonal flow exhibits a larger amplitude in the Southern hemisphere, especially at high latitudes, coinciding with a larger magnetic activity in that hemisphere.

3. Meridional Circulation
Describing the meridional circulation profile in depth, as well as its variation with the solar cycle, is one of the major goals of local helioseismology. The estimated amplitude of the meridional flows at the base of the convection zone is 1.2 m s\(^{-1}\) [8], too small to be detected by current helioseismic methods. Yet recovering a profile of the circulation to the maximum depth allowed by the observational techniques is crucial for the understanding of the dynamo complexity. The first attempt to use ring-diagram analysis to measure meridional circulation in 1999 by González Hernández et al. [9] showed the capability of the method for such studies. The flows recovered with limited data showed poleward velocities in each hemisphere, but the maximum amplitude was quite large compare to later investigations.

Basu & Antia (2003) [10] applied ring-diagram analysis to approximately 2-month data sets from 1996 to 2002 to study the temporal variation of the meridional flows with the solar cycle. They found a systematic time variation of the meridional flow: the maximum velocity of the

![Figure 1. Rotation rate for several latitudes (0°, 15°, 30° and 45°) from global analysis (thick solid line) and from ring diagrams (GONG solid thin line, MDI dashed thin line). The left panel shows the results obtained using the typical 15°-diameter areas, the right panel the same results using the larger 30°-diameter areas.][5]
flow is smaller when the Sun is more active (see Figure 4).

The time-distance technique has indicated a subsurface, reverse meridional flow cell developing at higher latitudes during the rising phase of the solar magnetic cycle [11]. Haber et al. (2002) [3] also found an equatorward meridional cell above 30° in the Northern hemisphere by applying ring-diagram analysis to the same period of time. They refer to the reverse flow as the “countercell.” (see Figure 5)

Following that discovery, McDonald & Dikpati (2004) [12] presented a meridional circulation model that included multicell formation, which would prevent the buildup of strong poloidal field predicted by the single-cell meridional circulation dynamo theories.

González Hernández et al. (2006) [5] applying large-aperture ring diagrams to a 2-year series of data confirmed the countercell in the northern hemisphere, but found a periodic appearance of similar countercells in the northern and southern hemisphere that correlates with maximum values of the B₀ angle (see Figure 6). The results lead to the conclusion that geometric calibration issues or the analysis method may affect the meridional circulation measurements from local analysis systematically at high latitudes where the countercell appears.

4. Flows around active regions and filaments

In recent years, ring-diagram analysis has also been used to investigate the local flows around active areas. An aspect that has been of particular interest is the finding by several local helioseismology techniques that strong active regions show convergent horizontal flows close to the surface but divergent flows at greater depth. Komm et al (2005) [13] study this behavior from the variation of the vertical velocity component, which is derived from the divergence of the
horizontal flows and shows a transition from downflow to upflow (see Figure 7). An important question is whether this change from convergent to divergent horizontal flow or change from downflow to upflow might be some kind of artifact. Haber et al. (2004) [14] checked whether the divergent flows at greater depth might be caused by the combined effect of the near-surface flows and the inversion technique used and found that a different choice of inversion technique did not alter the results.

Hindman et al. (2006) [15] used a customized version of the ring-diagram analysis method, that they named high resolution ring analysis (HRRA), to study the flows around filaments. They used the same tracking and tiling scheme for efficiency. However, instead of performing the ring analyses on each tracked tile, and achieving the standard measurement resolution of 16°, each of the large tracked regions is dissected into a multitude of smaller tiles. The flows were measured on two different submosaics: one is composed of square tiles that are 4° in heliographic angle on a side, while the other has tiles that are 2° on a side. Figure 8 shows the results from the 4° tiles. Their results seem to provide support for models requiring shear in order to form and maintain filaments, since they find complex cellular flows crossing the neutral line which implies magnetic field entanglements that are not an element in most simplified models.
5. Conclusions and future work
Ring-diagram analysis has made a significant contribution to the study of both large and localized velocity flows in the upper layers of the convection zone as exposed in the preceding sections. Recent work by Jain and collaborators [16] research the effect of the choice of spectral line in the results obtained by ring-diagram analysis. They use simultaneous observations from the Magneto-Optical filters at Two Heights (MOTH) taken at the South Pole (K and Na lines), and GONG (Ni line), opening the possibility for studying the material motions at different heights.

Because of the multiple applications of the technique, ring-diagram analysis is undergoing continuous modifications to improve the method. New developments include three dimensional kernels that have recently been developed by Birch et al. (2007) [17] for application in ring-diagram analysis. Efforts are also focused on investigating artifacts such as the systematics at high latitudes, that remain unexplained and need a detailed investigation. Komm et al. (2004) [17] noticed a strong correlation between measurement errors and magnetic flux at depths where active regions show upflows (or divergent horizontal flows), which makes measurement errors another potential source of artifacts.

Future missions like the Helioseismic and Magnetic Imager (HMI) on board SDO with a higher spatial resolution present new opportunities for local helioseismology in general and for ring-diagram analysis in particular.

6. Acknowledgements
I want to thank R. Bogart, T. Corbard, J. Bolding, R. Larsen and C. Toner for their valuable contributions to both the MDI and GONG RD pipeline code. This work utilizes data obtained by the Global Oscillation Network Group (GONG) program, managed by the National Solar Observatory, which is operated by AURA, Inc. under a cooperative agreement with the National Science Foundation. The data were acquired by instruments operated by the Big Bear Solar Observatory, High Altitude Observatory, Learmonth Solar Observatory, Udaipur Solar
Figure 5. Meridional flow averaged in time and longitude, shown as a function of latitude and depth for Dynamics Program intervals in the past six years. Underlying the vector fields are contours of constant meridional flow, with contours labeled in m s\(^{-1}\). Regions of southerly flow are indicated by negative contours and are shaded gray. Starting in 1998, an additional circulation cell appears in the northern hemisphere (positive latitudes). Courtesy of D. Haber [3].

Figure 6. Meridional flow contours at 0.96 R\(_\odot\) (~26 Mm). The approximate value of the B\(_0\) angle at the center of Carrington rotations 1987, 1994, 2000, and 2007 has been plotted on the upper axis for reference. Note that the counter-cells are centered at high values of B\(_0\) (the maximum value of B\(_0\) is 7.3), and that this angle varies with a 1 yr periodicity. [5]

Observatory, Instituto de Astrofísica de Canarias, and Cerro Tololo Interamerican Observatory. MDI (SOHO) is a project of international cooperation between ESA and NASA.
Figure 7. Average vertical velocity components as functions of latitude and depth (left: zonal flow; right: meridional flow). Top: Residual flows after removing the average polynomial fit. Middle: Residual flows averaged over locations of low activity. Bottom: Residual flows averaged over locations with flux values greater than 71 G. The dashed lines indicate the zero contour; the dotted lines indicate 20%, 40%, 60%, and 80% of the minimum and the maximum of the color scale. The velocity scale of the bottom panels is twice the size of that of the other ones. The dots indicate the depth-latitude grid. For the meridional flow, positive (negative) values indicate flows to the north (south).

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Figure 8. Daily high-resolution flow maps obtained using 4°-diameter tiles. The maps span four consecutive days: (a) 2002 March 30, (b) 2002 March 31, (c) 2002 April 1, and (d) 2002 April 2. Regions of opposite magnetic polarity, as determined from MDI magnetograms, are indicated in green and red. The dark contour line shows the position of a filament as observed in BBSO H images. On March 31 when BBSO images were unavailable, the contour from the previous day is indicated with a dashed line. Four long-lived convection cells span the location of the filament and are marked with numerals I to IV (in white). The filament runs through the center of these cells and the apparent flow along the neutral line is complicated. The widening of the filament over the span of the four days is probably due to projection of the filament against the solar disk as the region rotates across the Sun’s visible surface. Courtesy of B. Hindman [15]