ZONALLY AVERAGED MERIDIONAL FLOWS DETERMINED FROM LONG-TERM "RING-DIAGRAM" ANALYSIS

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ABSTRACT

Ring-diagram analysis ordinarily relies on tracking of the targeted regions of study in order to distinguish the physical targets spatially and to remove the large contribution of solar rotational velocity to the frequency splittings in the east-west direction. This has two disadvantages, that the time period for analysis is limited to a disc passage, and that the targeted region moves through the field of view, undergoing changes to the foreshortening and possibly geometric distortions. In an attempt to overcome these difficulties and improve on the sensitivity of the mean zonal and vertical structure of flows inferred from spatial and temporal averaging of results from traditional ring-diagram analysis, we have begun to analyze *untracked* regions for periods up to a full solar rotation. We report on initial results from analysis of the meridional flows from several full rotations of MDI Doppler data during selected Dynamics Campaigns, and compare the new results with those of traditional analyses.

1. INTRODUCTION

Ring-diagram analysis ordinarily relies on tracking of the targeted regions of study in order to distinguish the physical targets spatially and to remove the large contribution of solar rotational velocity to the frequency splittings in the east-west direction. This has two disadvantages, that the time period for analysis is limited to a disc passage, and that the targeted region moves through the field of view, undergoing changes to the foreshortening and possibly geometric distortions due to uncorrected optical field effects. These difficulties can be overcome, and the sensitivity of differential and absolute frequency measurements substantially improved, if we are willing to forego the longitudinal resolution provided by tracking.

Standard ring-diagram analysis of data from the annual 2–3 month Dynamics campaigns of MDI from 1996 through 2003 has revealed a surprising feature in the zonally averaged meridional flows, with a reversal of the meridional flow direction in the northern hemisphere only at depths greater than about 5 Mm in some years (see Haber *et al.*, 2002). In an effort to determine whether this feature is real or an artifact caused by projection effects, we examine the zonally- averaged meridional flow structure for selected times when the feature has and has not been present in the standard analyses.

Table 1. Rotations analyzed.

Carr. Rot.	Dates	B_0 Range
1910	1996 June 1–29	$[-0.7, +2.7]$
1921	1997 June 18 – July 15	$[+1.4, +4.3]$
1948	1999 Apr. 4 – May 1	$[-6.4, -4.3]$

2. DATA ANALYSIS

We have so far analyzed MDI Doppler data from three complete Carrington rotations contained in the MDI Dynamics campaigns of continuous full-disc resolution coverage. These are listed in Table 1. The first two rotation correspond to periods of comparatively low solar activity when the mean meridional circulation determined from the earlier ring diagram analyses of Haber *et al.* (2002) was simple and symmetric, while the last is from a time when the unexpected counterflow in the meridional circulation at depths of about 10 Mm and below was first seen.

The data were untracked in the sense that longitudes were referred to the central meridian of epoch, but corrections were made for the drift of the spacecraft in heliographic latitude in the course of the observing period, which amounted to an equivalent surface velocity of 15 m/s during the first two campaigns and 10 m/s in the third. The analysis interval in each case was 39,664 minutes (24×1664 min) centered on the time of central meridian

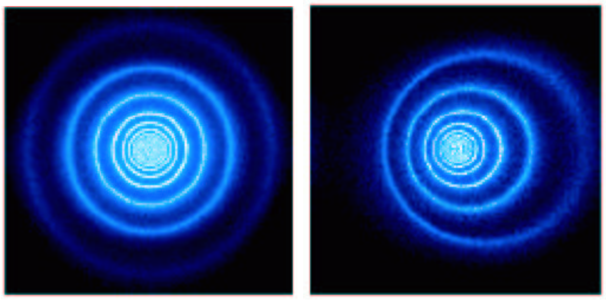

Figure 1. Samples of tracked and untracked ring power spectra. The ring diagram on the left is from an average of 24 1664-minute tracked power spectra near disc center. That on the right is from a single 39,936-minute untracked spectrum near disc center. Both are cuts through the 3-d spectra at frequencies around 3 mHz and represent data for one Carrington rotation. (The power in the untracked spectrum has been frequency-averaged to the same frequency resolution.)

crossing of Carrington longitude 180° of the appropriate rotation as viewed from SOHO. A sample of a "ring-cut" through one of these spectra, together with a normal comparison ring diagram, are shown in Fig. 1. Power spectra were obtained in 15°-wide bins at latitudes between ±67°.5 in steps of 7°.5.

The displaced ring spectra were fit using the same 13-parameter fit we have used for tracked ring spectra (Basu & Antia, 1999), with suitable adjustments for the anomalously large values of the U_x parameter reflecting the advection of the waves by solar rotation. The fits for the U_y parameter measuring meridional motion were inverted for depth structure using OLA inversions. Those inversions are plotted at selected latitudes for each of the rotations analyzed in Figs.2–4. For comparison we also show inversions of the same parameter from fits to averages of the twenty-four 1664-min tracked spectra for meridian crossings of all the longitudes at 15° intervals in the rotation as they crossed the central meridian. The northern hemisphere reversal during CR 1948 can be clearly seen in these comparison results, though the result of Haber *et al.* (2002) was based on a different procedure, averaging the fit parameters for individual spectra obtained over a range of central meridian longitudes between ±45°.

3. RESULTS

The inverted values for the meridional advective term U_y for each of the three rotations analyzed are shown in Fig.2–4. For comparison the values obtained with the normal tracking and averaging of 24 successive 'days' are also plotted.

The agreement between the zonally averaged tracked data and the untracked data for CR 1910 and 1922 is very close. The most significant discrepancy appears to be just below the surface (∼ 3 Mm) at higher southern latitudes,

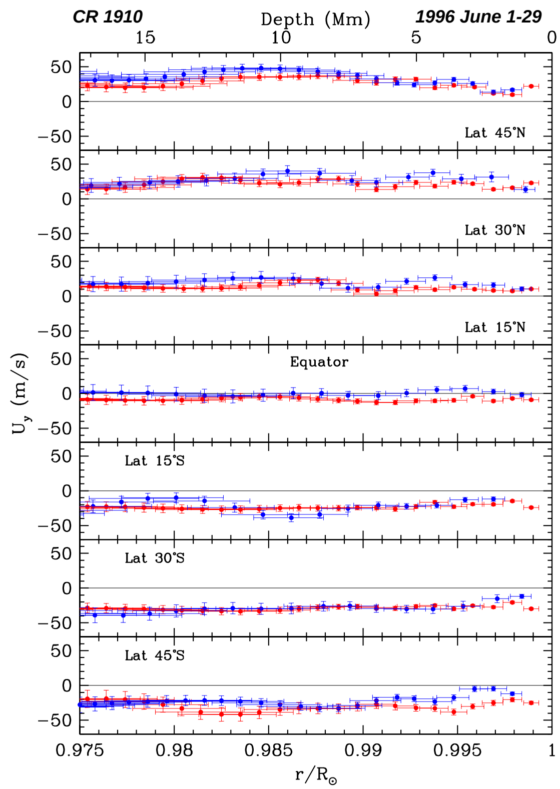

Figure 2. Values of the meridional velocity parameter U_y as s function of depth at representative latitudes for CR 1910. Untracked results are plotted in blue, 24-sample averages of the tracked results in red.

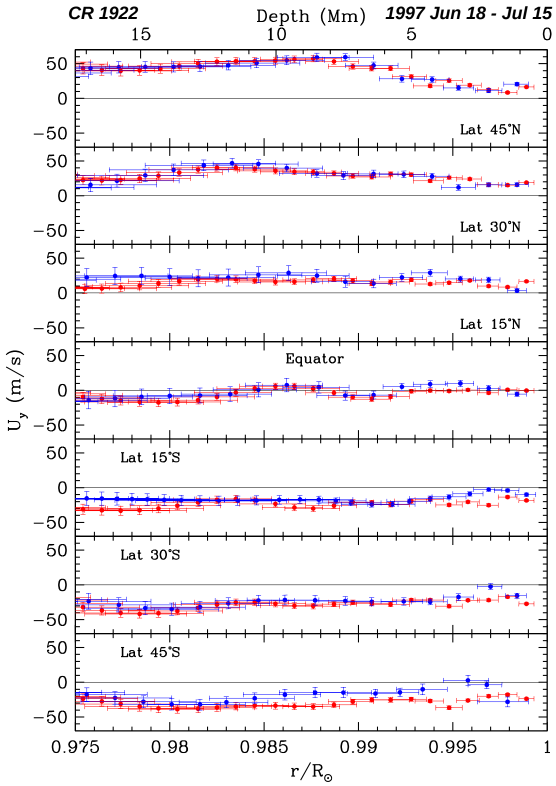

Figure 3. Same as Fig.2, for CR 1922.

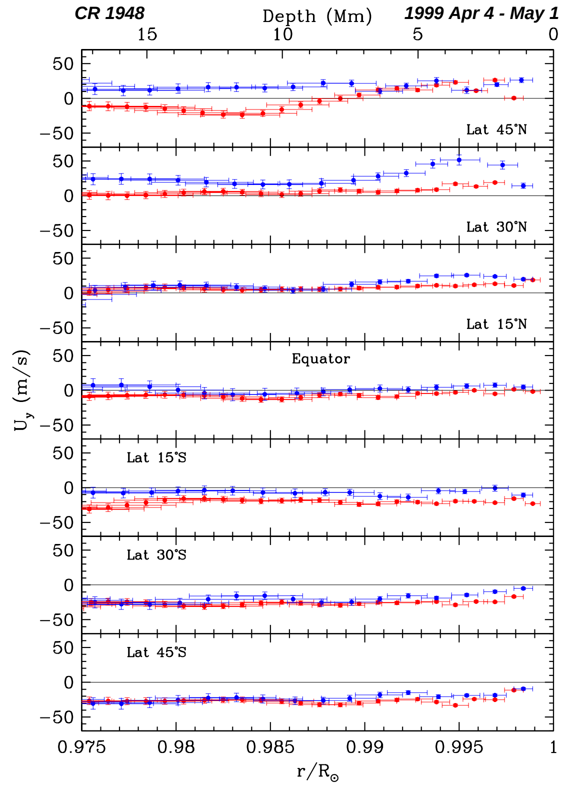

Figure 4. Same as Fig.2, for CR 1948.

where the untracked results show a significant weakening or even disappearance of the general poleward flow.

For CR 1948, the northern hemisphere reversal of the meridional flow at depths > 7 Mm seen in the tracked data is not present in the untracked data. On the other hand, there is evidence for a shallow poleward "jet" of amplitude ~ 50 m/s at a depth of 3–5 Mm in northern hemisphere mid-latitudes ($\sim 30°$).

The discrepancies between the results for tracked and untracked data could be due to longitudinal structure in the meridional flow that is not linearly averaged into the zonal mean for the whole rotation, or to the effects of differential foreshortening and uncorrected image distortion as the tracked regions move across the images. In order to eliminate longitudinal structure in the flows as the source of the discrepancies, we have compared the untracked results at high northern latitudes with those of several tracked averages extending over only one-third of a Carrington rotation (120°, $\sim$ 9 days) during CR 1948. Comparisons of the results for latitudes 30° and 45° north, where the effect is largest, are shown in Fig.5. Although the meridional countercell seen in the tracked data varies somewhat in amplitude and structure, the effective disappearance of the poleward flow at a depth of $\sim$ 7 Mm is always present in the tracked data, and the discrepancies with the untracked data are always present and of the same sign. Similarly, the near-surface jet seen in the untracked data is not present in any zonal sector for the tracked data.

4. CONCLUSIONS

If we are willing to forego longitudinal resolution, ring-diagram analysis for zonally-averaged structures using traditional techniques applied to untracked data appears to be fully feasible and produces results of comparable quality even in the absence of special modifications to the fitting procedures.

The zonally-averaged meridional flow structure determined with the present method agrees well with that determined by tracking, except that the anomalous reversal at depth in the northern hemisphere seen in the tracked results in Apr. 1999 is not seen. Instead, there is evidence for a shallower layer of enhanced poleward flow at slightly lower latitudes. Because the reversal is seen in tracked data for sub-intervals throughout the rotation, its presence in the zonal averages can probably not be explained by a sectoral structure. We consider it likely that the explanation for the inferred counterflow lies in the geometric distortion of the tracked regions as they drift across the field of view, due to uncorrected optical distortion, geometric foreshortening, and/or mode-mixing as the directions of the local geodesics on the remapped data change in time. The importance of these effects is also suggested by the fact that the reversal is seen in the data observed at maximum southerly heliographic latitude (Table 1), when the affected zones are furthest from disc center.

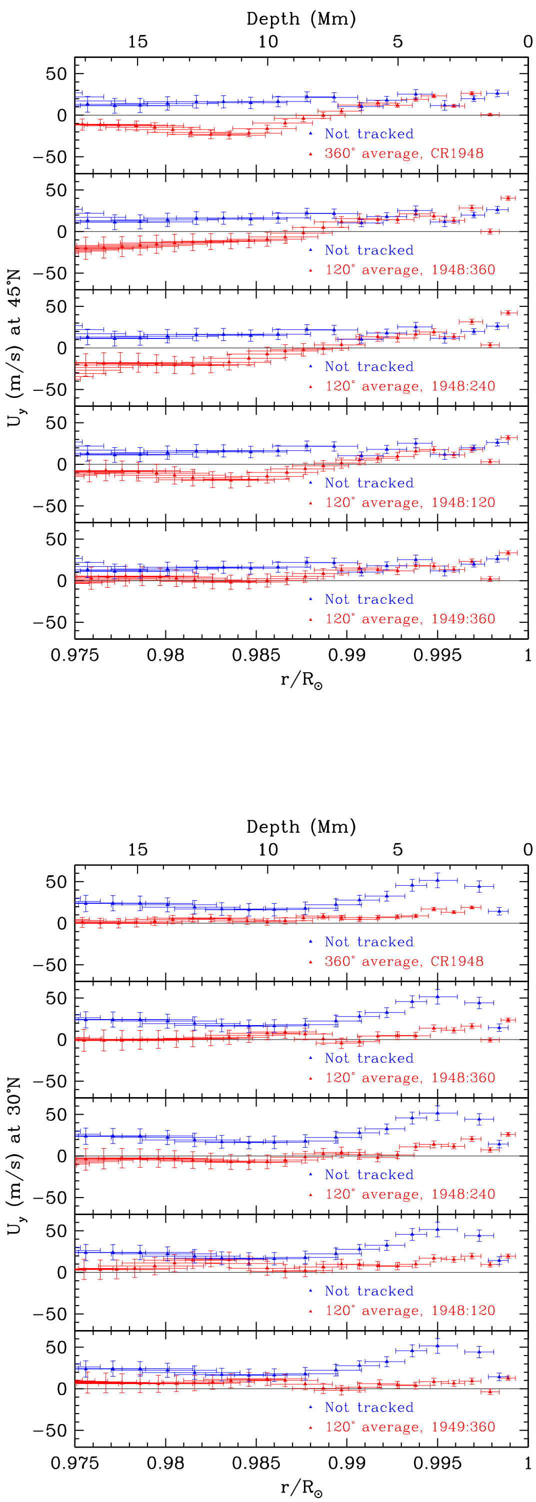

Figure 5. *Values of the meridional velocity parameter U_y as a function of depth at latitudes 45°N (above) and 30°N (below) for CR 1948. Untracked results for the full rotation are plotted in blue, those for the 24-sample and successive 8-sample averages of the tracked results in red.*

ACKNOWLEDGMENTS

This work utilises data from the Michelson Doppler Imager (MDI) on SOHO. SOHO is a project of international cooperation between ESA and NASA. The MDI project is supported by NASA contract NAG5-13261 to Stanford University. This work was supported in part by NASA grant NAG5-10912 to SB..

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