Sub-surface Meridional Flow Results from MWO, GONG, and MDI during Solar Cycle 23

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Introduction

Time series of full-disk Dopplergrams were acquired at the 60-Foot Solar tower of the Mount Wilson Observatory every year between 1987 and 2009. The 60-Foot Tower was designed by George Ellery Hale to provide an image plan that did not rotate throughout each observing day. However, preliminary analyses that began in 2007 of a portion of this archive revealed that the focal plane of the Tower did experience a small amount of systematic rotation, which suggested that the alignment of the optics had changed slightly over the years since 1907. This instrumental rotation of the image plane was discovered through the computations of subsurface flow maps using the ring-diagram method of local helioseismology. Some of the initial daily flow maps appeared to show evidence for a so-called “washing machine” effect similar to the pattern that was seen in raw GONG flow maps. Previous work has been done to try compute the magnitude of the spurious rotation. An auto-correlation technique revealed a rotation rate of approximately 0.018 degrees per hour whereas a cross-correlation with MDI data revealed as 0.0117 degree per hour rate. Analysis of the North-South flow asymmetries for individual Carrington Rotations suggests the zonal flows are affected by the image plane rotation rate whereas the meridional flow is relatively unaffected [Pinkerton, et al., 2013]. Preliminary comparisons of the asymmetries in the zonal flow with those from MDI and GONG suggest the image plane rotation rate is lower than previously calculated: in 0.004+-0.002 degrees per hour.

Data and Analysis

During Solar Cycle 23, the most publicized local helioseismic data was gathered using the Michelson Doppler Image (MDI) on board Solar and Heliospheric Observatory (SoHO) and the Global Oscillation Network Group (GONG, later GONG+). There is also a wealth of high-resolution, ground-based information taken from the 60-Foot Tower at the Mount Wilson Observatory (MWO) during Solar Cycles 22 and 23 that has yet to be fully analyzed by the helioseismology community. Observations were obtained on a total of 4624 days during the 23 annual observing campaigns, of which 3643 days were found to be usable. The duty cycle during SC 23 is shown below in Figure 1.

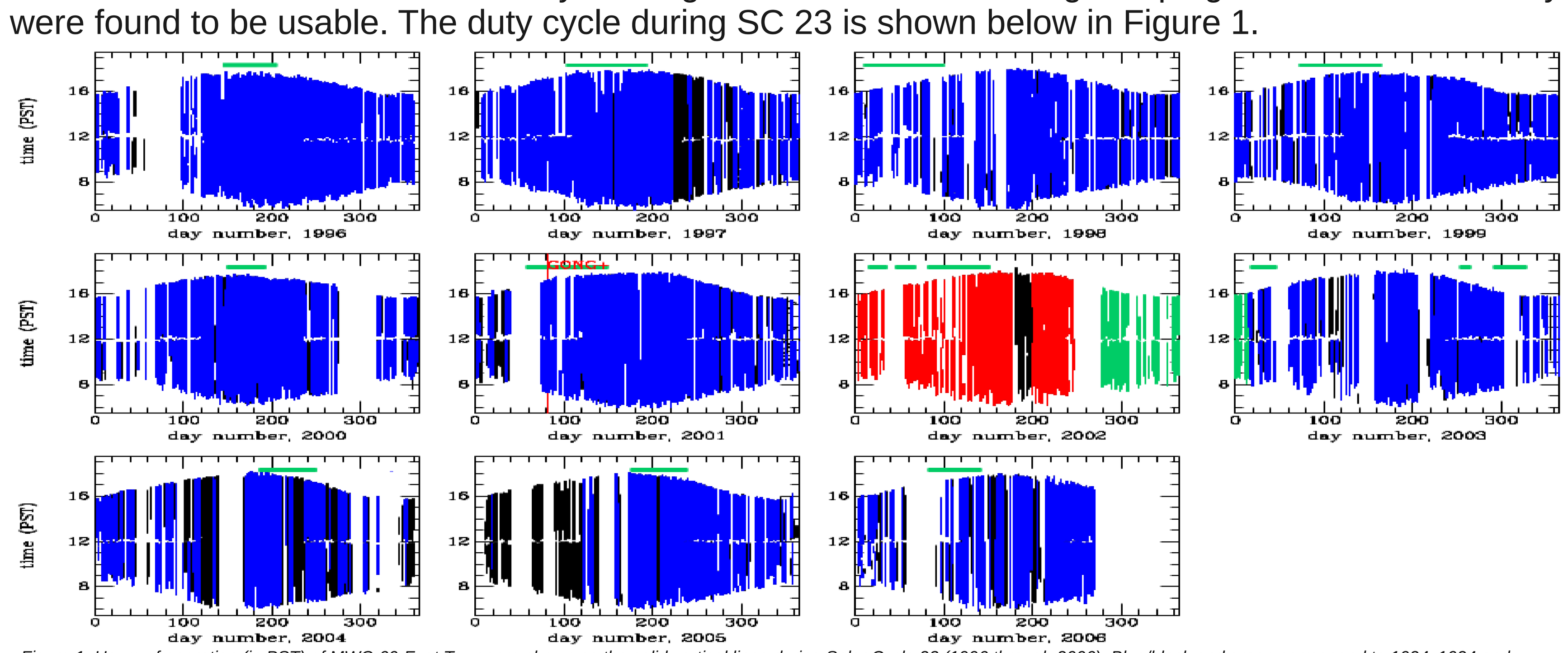

Figure 1: Hours of operation (in PST) of MWO 60-Foot Tower are shown as the solid vertical lines during Solar Cycle 23 (1996 through 2006). Blue/black and green correspond to 1024x1024 and 512x512 pixels, respectively; the CCD camera was not outputting all rows from each frame during the red region in 2002. For comparison, the annual MDI Dynamics Runs are shown as the horizontal green bars near the upper boundaries of the panels and the date of the beginning of GONG+ observations during 2001 is shown by the vertical red line.

The method we use to analyze the MWO data is ring diagram (RD) analysis [Hill, 1988]. Pairs of images are taken of the sun at a cadence of one pair per minute for up to 11 and 2/3 hours per day (resulting in 700 pairs per day) using one of two cameras (a 1024x1024 pixel CCD camera and a backup 512x512 Panasonic video-rate camera) and a Magneto-Optical Filter (MOF) using one of two spectral ranges (Na I D-lines, 589.6-589.0 nm, or K I line 769.9 nm). The Dopplergrams that are produced in this manner are archived at Stanford where we use a modified MDI/HMI software pipeline to generate and fit the power spectra, as out lined in [Haber, et al., 1998]. The inversions are then done using the OLA technique to produce zonal and meridional flow profiles.

Due to the instrumentally-induced image plane rotation, Dr. Richard Bogart made a modification to the program that he had developed to track different portions of the solar disk for use with the MDI images so that this tracking program could remove the effects of an assumed instrumental rotation rate. Thanks to this modification, we have been able to both correct for the image rotation in the MWO data as well as explore the effects of image rotation by under- and over-compensating for the correction.

Effects on Zonal and Meridional Flow

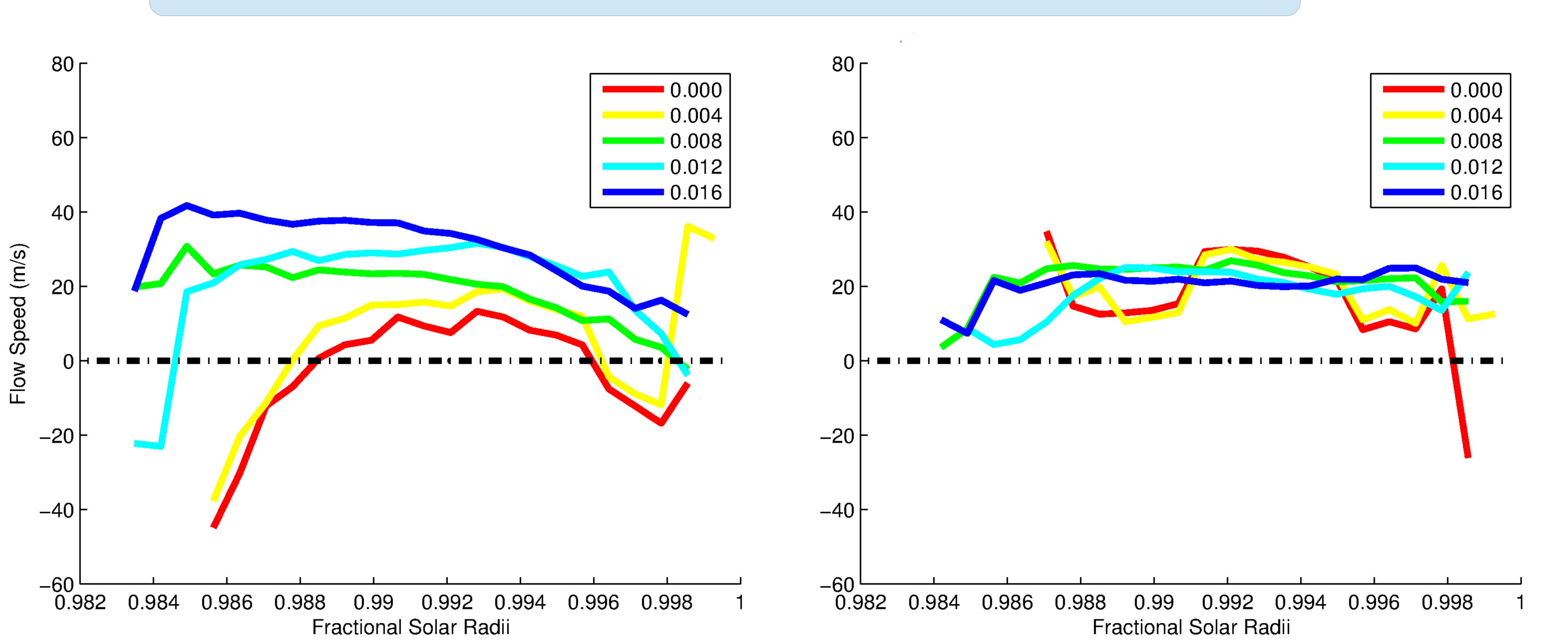

Figure 2: Subsurface flow speeds from inversions of MWO data plotted as functions of solar radii at latitude 30 North during Carrington Rotation 1949. The tracking of the MWO data was corrected using five possible focal plane rotation rates: 0.000, 0.004, 0.008, 0.012, and 0.016 deg/hr. a.(left) The Zonal component of the flow shows a significant dependence on the chosen rotation correction. b.(right) The meridional component does not show any such dependence.

We have been tracking Dopplergrams and then fitting and inverting flow maps using the five assumed image plane rotation rates in the range 0.008 to 0.016 deg/hr; however, preliminary analysis of these correction rates suggested that we needed to explore smaller rotation correction rates: 0.000 and 0.004. Figure 2 shows (a) the zonal and (b) meridional components of the subsurface flows for all five of these assumed rotation rates at latitude 30 North averaged over Carrington Rotation (CR) 1949, or May 1 - May 27, 1999. The zonal flow is significantly affected by the choice in rotation correction, as can be seen by the separation of the curves in the northern hemisphere as depth increases in Figure 2a. This separation, where a higher rotation correction results in a more positive flow, is mirrored for zonal flows in the southern hemisphere. The meridional flow is relatively unaffected by the image plane rotation rate compared with the zonal flow; however, small residual differences are present between the different image plane rotation rates.

Differences in Zonal and Meridional Flows between Hemispheres

Since an image plane rotation influences the zonal flows in opposite directions in the northern and southern hemispheres, such an instrumental rotation will introduce a difference in the magnitude of the zonal flows in the two hemispheres. We define the ``spread'' to be the difference in magnitudes between the northern and southern hemispheres for both flow components. As shown in Figure 3a, the MWO zonal spread strongly depends on the assumed instrumental rotation rate (pluses).

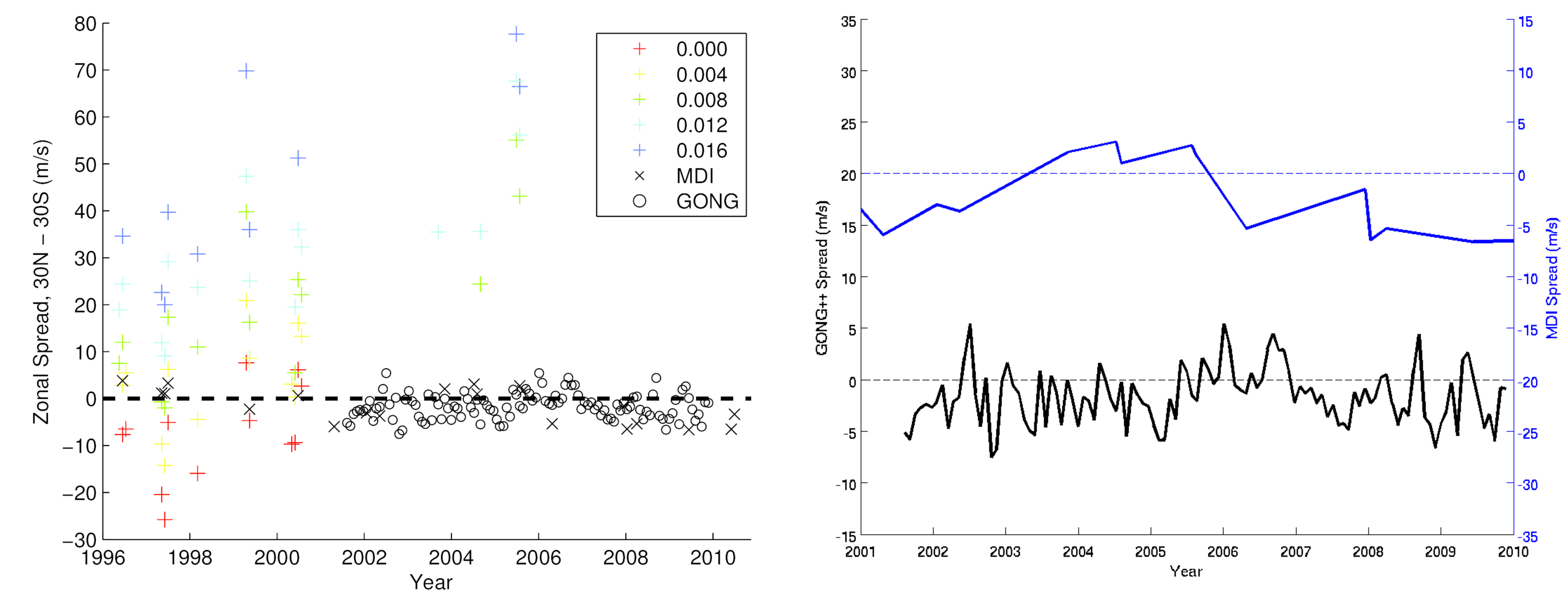

Figure 3: Plots of the differences in the zonal flow component between the northern and southern hemispheres at latitude +-30 as functions of time. a.(left) Scatter plot of MWO (pluses), MDI (Xs) and GONG+ (open circles) data. b.(right) Plot of the spread for MDI (top curve, right axis) and GONG+ (bottom curve, left axis) during years 2001-2009. Note there is a 20m/s vertical offset between the two curves.

The MDI (Xs) and GONG+ (open circles) zonal spreads reveal a relatively small difference in their northern and southern zonal flows. Additionally, it is apparent that for small, non-negative values of the rotation correction, the MWO zonal spread is also nearly zero. On closer inspection of the MDI and GONG+ data in Figure 3b, we can see that both MDI and GONG+ have predominantly negative spread values meaning that the southern hemisphere had the marginally larger magnitude zonal flows for most of this time period.

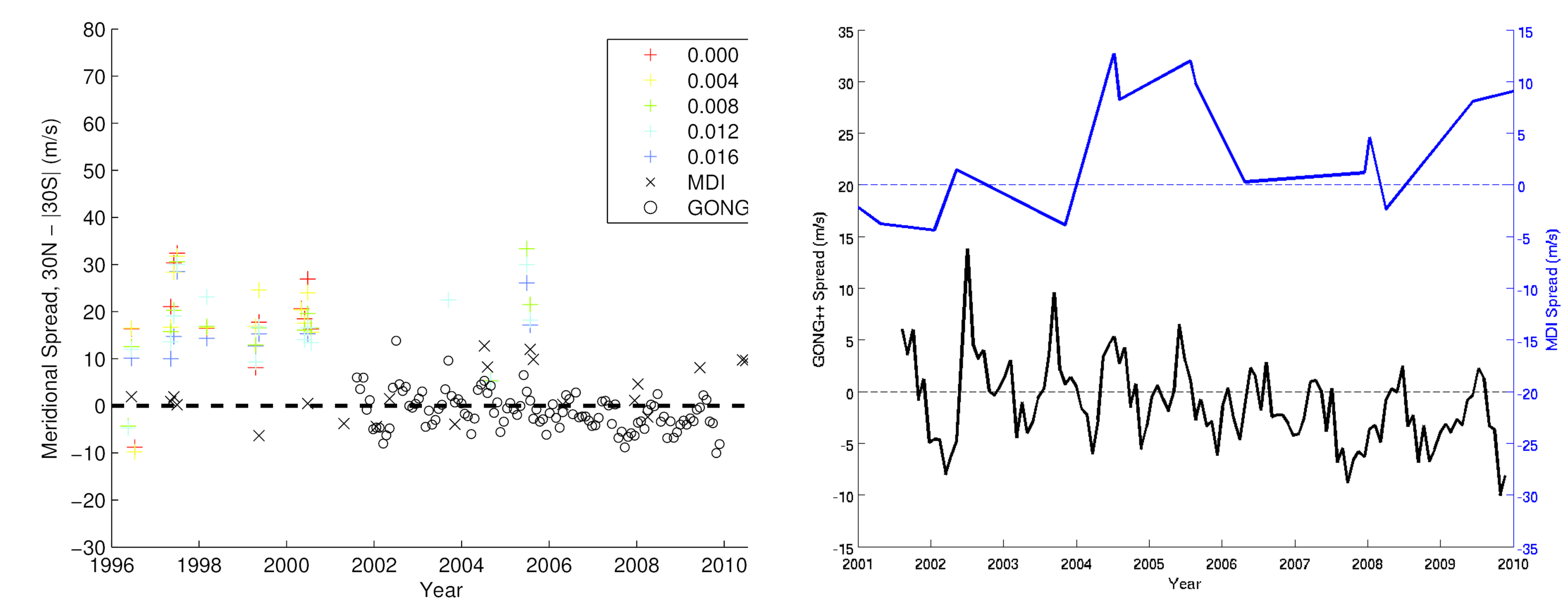

Figure 4: Plots of the differences in the meridional flow component between the northern and southern hemispheres at latitude +-30 as functions of time. a.(left) Scatter plot of MWO (pluses), MDI (Xs) and GONG+ (open circles) data. Unlike the zonal flows, the meridional flows do not depend systematically on the image plane rotation. b.(right) Plot of the spread for MDI (top curve, right axis) and GONG+ (bottom curve, left axis) during years 2001-2009. A clear oscillation pattern is visible in the GONG+ data in the right panel. Note the 20m/s vertical offset between the two curves.

As expected from the previous section, and as seen in Figure 4a, the meridional flow component does not vary in a systematic manner with respect to the image plane rotation. Nevertheless, Figure 4a suggests we are estimating a consistently stronger poleward flows in the northern hemisphere than the southern.

In the GONG+ plot of Figure 4b, there is a clear annual periodicity to the magnitude of the spread. This suggests that the GONG instrument observes the meridional flows to be stronger in the northern hemisphere in the summer and weaker in the winter. There is a steady decline in the value of the spread from 2001 to 2009, which could be consistent with decreasing levels of solar activity. Neither of these traits are seen in the MDI data from the corresponding time frame. This may be due to the ground based nature of the GONG+ project, in which case we would expect to see similar patterns in the MWO data.

Processing Status

Beginning from April 2013, we have processed 1845 days of Dopplergrams, between January 2, 1996 and January 31, 2006, at both the 0.000 and 0.004 rotation correction rates using the previously mentioned ring diagram method. We plan to have the rest of the data set during 23 processed by the end of July and process the remaining days in SC 22 and SC 24 by Spring 2015 at image plan rotation correction rates of 0.000 and 0.004. Depending on the analysis of the complete data set at these rotation correction rates, we will cease or continue processing and the larger correction rates.

Conclusions and Future Work

Based on the results of this study thus far, it is becoming more apparent that the meridional flow does not depend heavily on the tiny image rotation rate of the 60' Solar Tower; however, the zonal flow is very dependent on the choice of rotation correction. The relative independence of the meridional flows on the image plane rotation gives us confidence that our estimates of the meridional flows will be robust. Of the rotation corrections we have analyzed thus far, it appears that the 0.004 deg/hr rotation correction rate may provide the most accurate zonal flow results.

We will be implementing a multi-ridge ring fitting technique developed by Benjamin Greer of Univ. of Colorado [Greer, et al., 2014] in the coming months. With the determination of the image plan rotation rate and the correction of this phenomenon, we will be able to resume using global helioseismology techniques to analyze this data (e.g. see [Rhodes, et al., 1998]. We will identify systematic errors in the observation and processing routines, including center-to-limb and spectral line effects.

References

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