Meridional-Flow Measurements from 15 Years of GONG Spherical-Harmonic Time Series

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Abstract. We present results of meridional-flow measurements for 1995–2009, using travel-time differences from velocity images reconstructed using GONG spherical harmonic (SH) coefficients after applying phase-velocity and low-m filters. This filtering technique increases the signal-to-noise ratio and thus extends travel-time measurements to relatively high latitudes and deep into the convection zone. Preliminary analyses shows a strong one-year periodicity presumably due to solar pole misalignment and $B_0$-angle artifacts, which makes it difficult to see underlying temporal variations. Removing a simple one-year-period sine wave fit reveals long-term temporal variations of the flow on top of this yearly periodicity. High-latitude measurements are affected more strongly by foreshortening and $B_0$-angle artifacts. We analyze different $B_0$-angle intervals separately, so in each hemisphere better high-latitude visibility comes six months apart. This approach suggests why at high latitudes travel-time measurements of meridional flow shows a tendency to change sign instead of continuing towards the poles.

1. Introduction
Meridional circulation transports surface plasma and magnetic field from low latitudes toward the solar poles, and as such plays an important role in the solar activity cycle [4]. According to many models, the speed of the meridional flow determines the length of near-future magnetic cycles, and therefore temporal variations of the meridional flow may play an important role in, or provide an important diagnostic of, variations of the activity cycle. Since the deep meridional flow is much weaker than solar rotation, the torsional oscillation, or active-region associated flows, measurement of temporal changes requires very precise, long-term observations, improving analysis technique and understanding systematic errors. During the last several years meridional circulation has been studied by different helioseismic techniques [1-3], [5-11].

Long term observations by MDI, GONG and TON instruments have provided detailed measurements of meridional flow and its temporal variations. In most helioseismic analyses using ring-diagram analysis, meridional-flow measurements have been studied for subsurface layers (not deeper than 30 Mm). Using SH time series allow us to extend our measurements much deeper, including the tachocline region.

2. Data and analysis technique
We use daily SH coefficients time series for $\ell = 0 – 200$ obtained by the GONG project during the 1995–2009 time period. Time series are organized as series of individual $(\ell, m)$ coefficients for 24 hour intervals. In this study, we have selected 3658 daily series with duty cycle higher than 80%.

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We apply time-distance technique to measure North–South travel-time differences on velocity images that have been reconstructed. Since we are interested in travel times for acoustic waves propagated in the North–South direction, isolating such waves increases the signal-to-noise. We call this procedure "low-m filtering". In other words, we keep only North-South component of the velocity signal and remove all the rest. Only 15% of the low-m coefficients of any $\ell$ are used to reconstruct the velocity images. In addition we also apply phase-velocity filtering to isolate waves propagating along the same ray path and having the same lower turning points in

![Figure 1](image.png)

**Figure 1.** Travel-time differences at $\theta=20^\circ$ for four angular separations ($\Delta$): raw (dots), fit (thin solid line) and filtered to remove the annual ($B$-angle) artifact (thick line): left column for southern and middle column for northern hemispheres. Right column shows symmetrized temporal differences in the two hemispheres and running one-year sine fit of yearly intervals. A consistent decrease is seen at solar maximum, which recovers more slowly closer to the surface.

In order to measure travel-time shifts due to meridional flow for different depths, we choose different phase speeds in our filtering process. Since standard GONG SH time series are limited to $\ell \leq 200$, our measurements cover $0.97 R_\odot$ and deeper layers.

### 3. Results and discussion
We found that travel times show a strong one-year periodic signal presumably due to the $B_0$-angle and foreshortening, and possibly a misalignment of the solar pole [6]. Measuring the temporal...
variations of the meridional flow is difficult in the presence of such a strong periodic signal. At high latitudes, this artifact changes the flow direction, which can easily be misinterpreted as a second-cell structure of meridional flow [8]. To extract the changes in time, we symmetrized the temporal differences in the two hemispheres and performed a running one-year sine fit of yearly intervals. The filtered and symmetrized signal in Figure 1 shows a solar-cycle like trend. For larger separations, we do not see any systematic variations, which would be expected if these systematics are related to surface activity. Often meridional flows measured by the travel-time

\[ \Delta = 7^\circ \]

\[ \Delta = 11^\circ \]

**Figure 2.** Travel-time difference for two angular separations: the entire time period (open circles), the 10% of the time with the South Pole most exposed (dots) and the 10% of the time with the North Pole most exposed (squares).

technique show decreasing magnitude at high latitudes starting at about 30° – 40°, which can lead to a scenario with a reversal of the poleward flow before reaching the poles. We analyzed averaged time differences during the two maximum $B_\theta$-angle time periods. In Figure 2 we show the average time differences for positive and negative tilt periods in comparison to the average signal for the entire time period. There is obvious evidence for the decrease of this effect in favorable tilt periods. To see the depth dependence of the time differences, we have averaged measurements over the whole time period. In Figure 3, measurements with different lower turning points are presented. With increasing depth, the magnitude of the travel-time differences increases until the tachocline region and then decreases. Due to the averaging for 15 years, the typical measurement error bars are less than 0.02 seconds. To get the actual flow
Figure 3. Travel-time differences for four angular separations. The magnitude of the travel-time differences increases for separations with lower turning point up to $0.76R_\odot$ and then decreases. Separation distances are proportional to lower turning points of the waves. These particular separation distances correspond to $0.97R_\odot$, $0.87R_\odot$, $0.76R_\odot$ and $0.67R_\odot$ respectively. $\Delta=45^\circ$ corresponds to the tachocline region ($\approx 0.71R_\odot$).

speed and depth profile of the flow, we need to use inversion techniques. Efforts on this task are in progress.

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