Time-distance measurements of meridional circulation using pairs of points at equal center-to-limb angle

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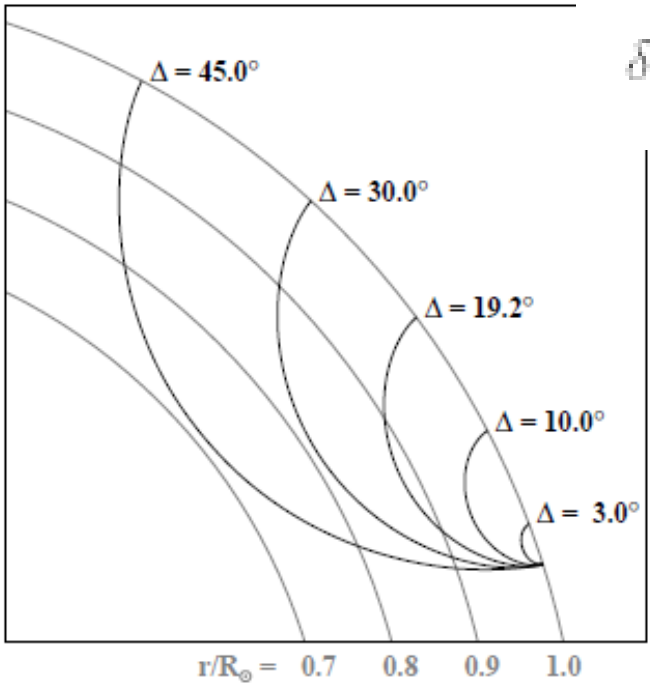
Examples of ray paths for measuring meridional circulation (left); expected travel-time differences for a single radial cell model (right)



$$\delta\tau \equiv \tau^{+} - \tau^{-} = -2\int_{\Gamma_0} \frac{\mathbf{u}\cdot\hat{\mathbf{n}}}{c^2}\,ds$$

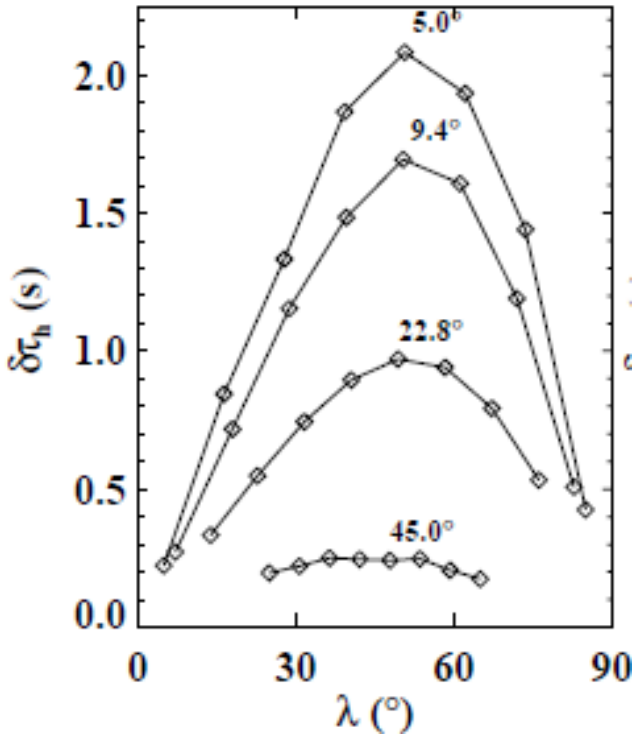
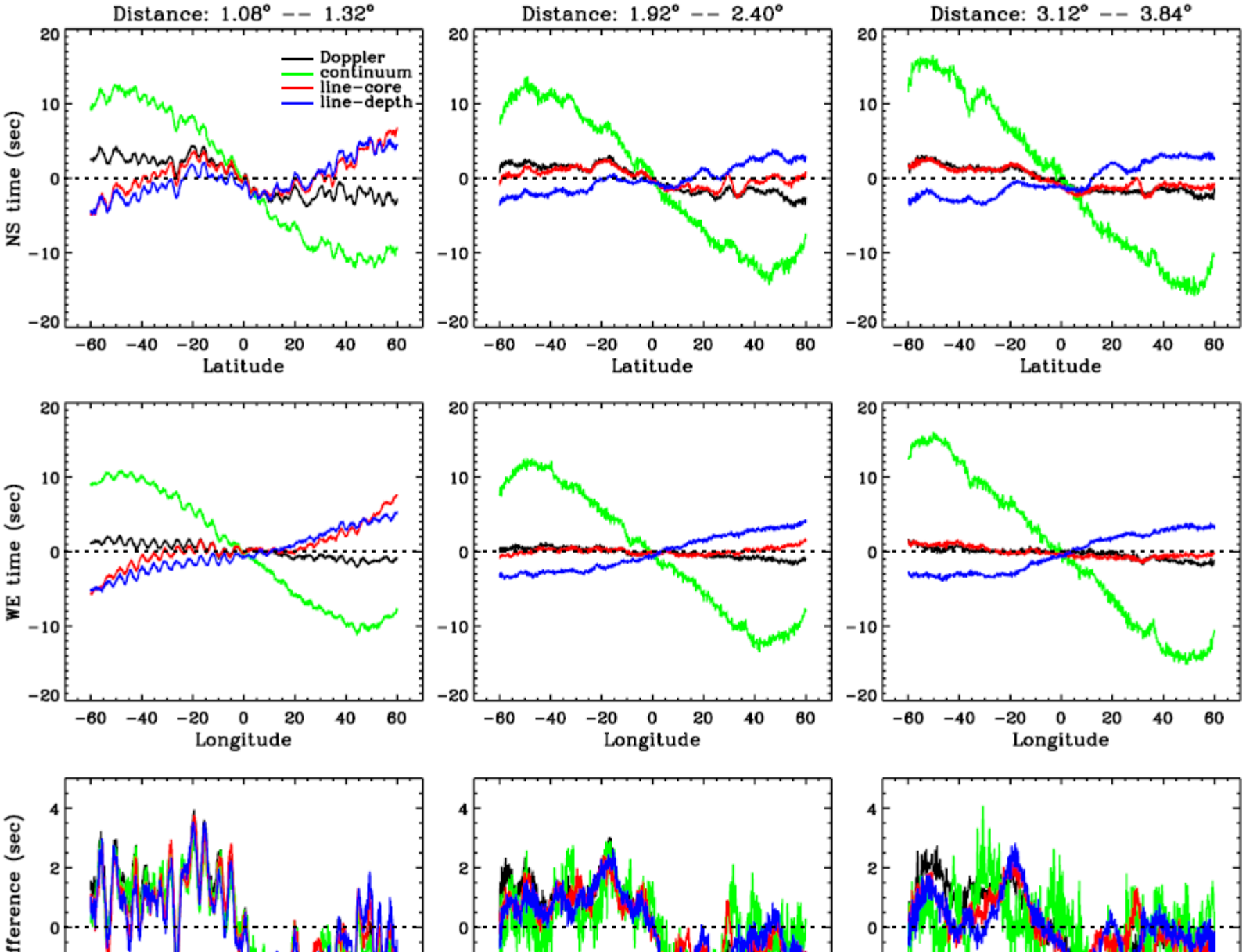


Figure 2.2: A great circle plane containing several sample rays. The grey arcs indicate the fractional radius, and the five black curves show the path taken by waves propagating in the convection zone. The largest ray shown travels a distance of 45° and reaches to $r = 0.71\,R_\odot$; this is the largest distance for which cross correlations were computed in this work.


Distance: 1.08° -- 1.32°
Distance: 1.92° -- 2.40°
Distance: 3.12° -- 3.84°
Doppler
continuum
line-core
line-depth
NS time (sec)
WE time (sec)
Latitude
Longitude
20
10
0
−10
−20
−60 −40 −20 0 20 40 60
4
2
0

The problem: east-west signal very similar to north-south

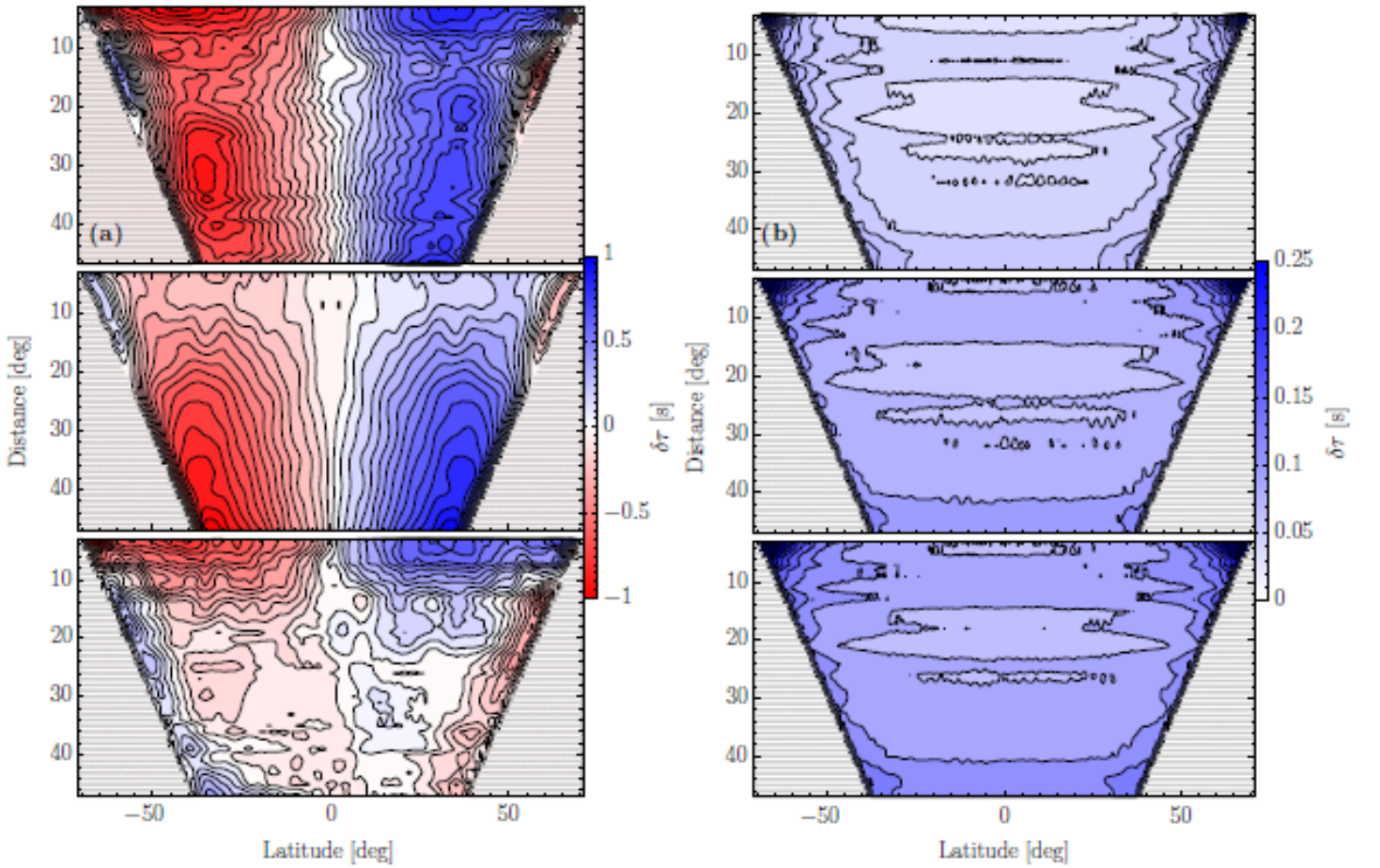


Figure 2. Travel-time difference maps obtained using 652 daily sets of Doppler velocity images. Column (a) shows the S-N, E-W, and S-NE-W contour maps from top to bottom, respectively. Column (b) plots the corresponding measurement uncertainties associated with each panel in column (a). Note the x-axis in the middle panel in each column is the longitude, with the same numerical scale values as shown for latitude ($\pm 75°$). Hatched regions show where no measurements were computed due to limb constraints.

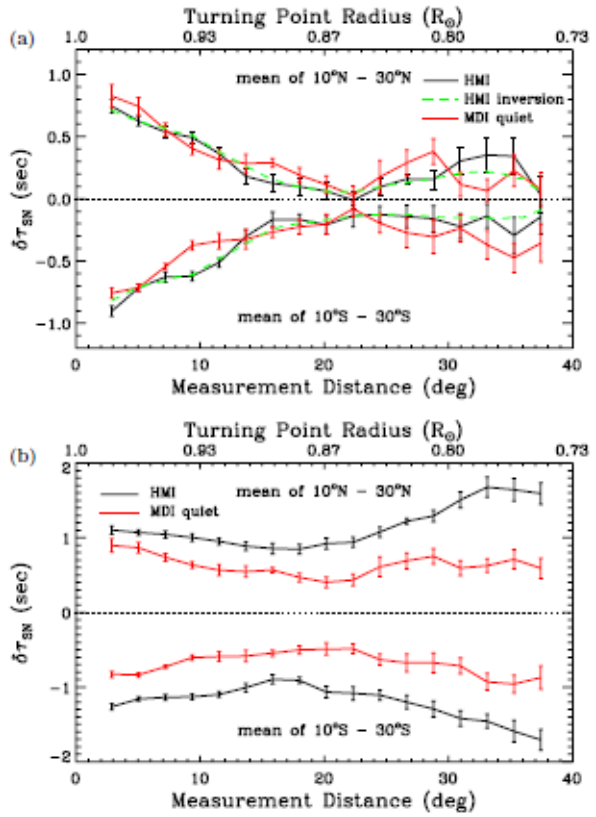
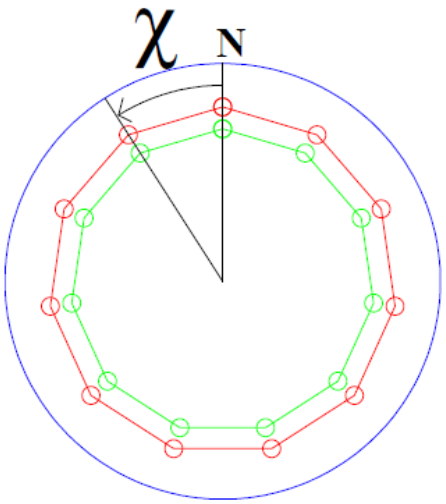


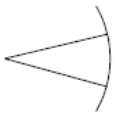
Figure 3. (a) Comparison of the measured acoustic travel-time differences, $\delta\tau_{SN}$, from the HMI and MDI data after removal of the systematic center-to-limb variations, together with the $\delta\tau_{SN}$ calculated from the interior velocity inverted from the HMI measurements. Error bars for the green dashed curves are similar to those for the black curves. (b) Comparison of the $\delta\tau_{SN}$ from the HMI and MDI quiet-period observations before the removal of the systematic effect.

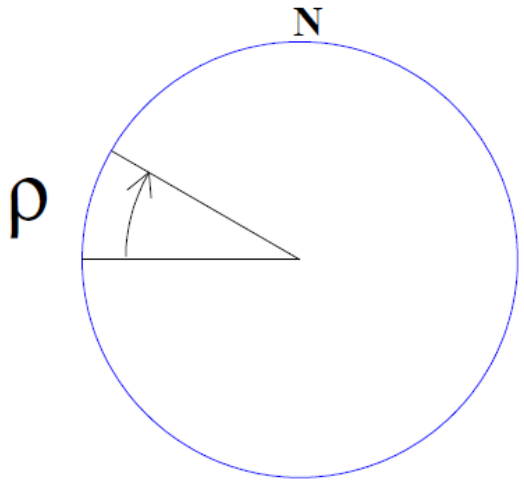
Geometry for measurement technique



χ = **azimuth east about north**

ρ = **heliocentric angle**

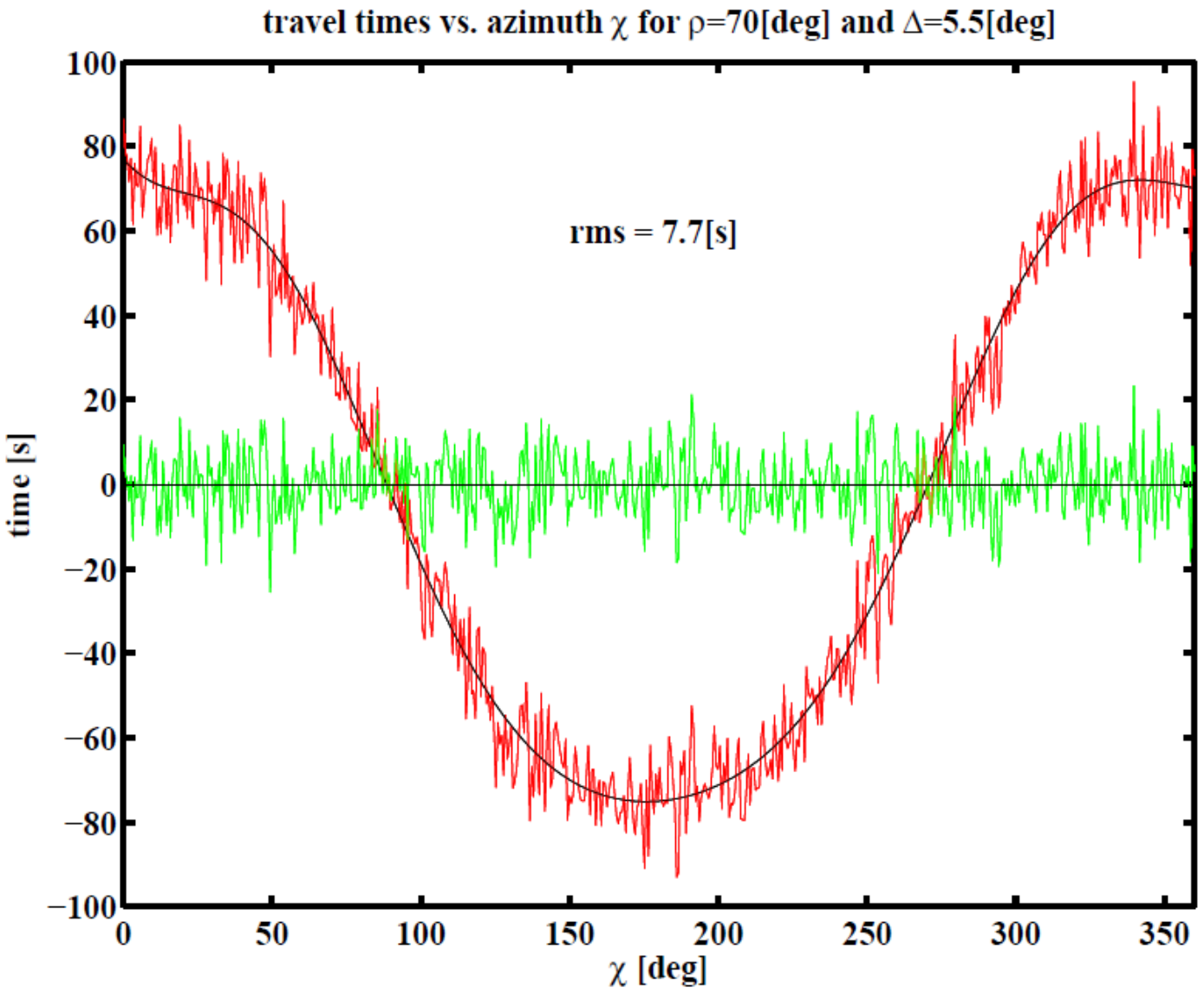




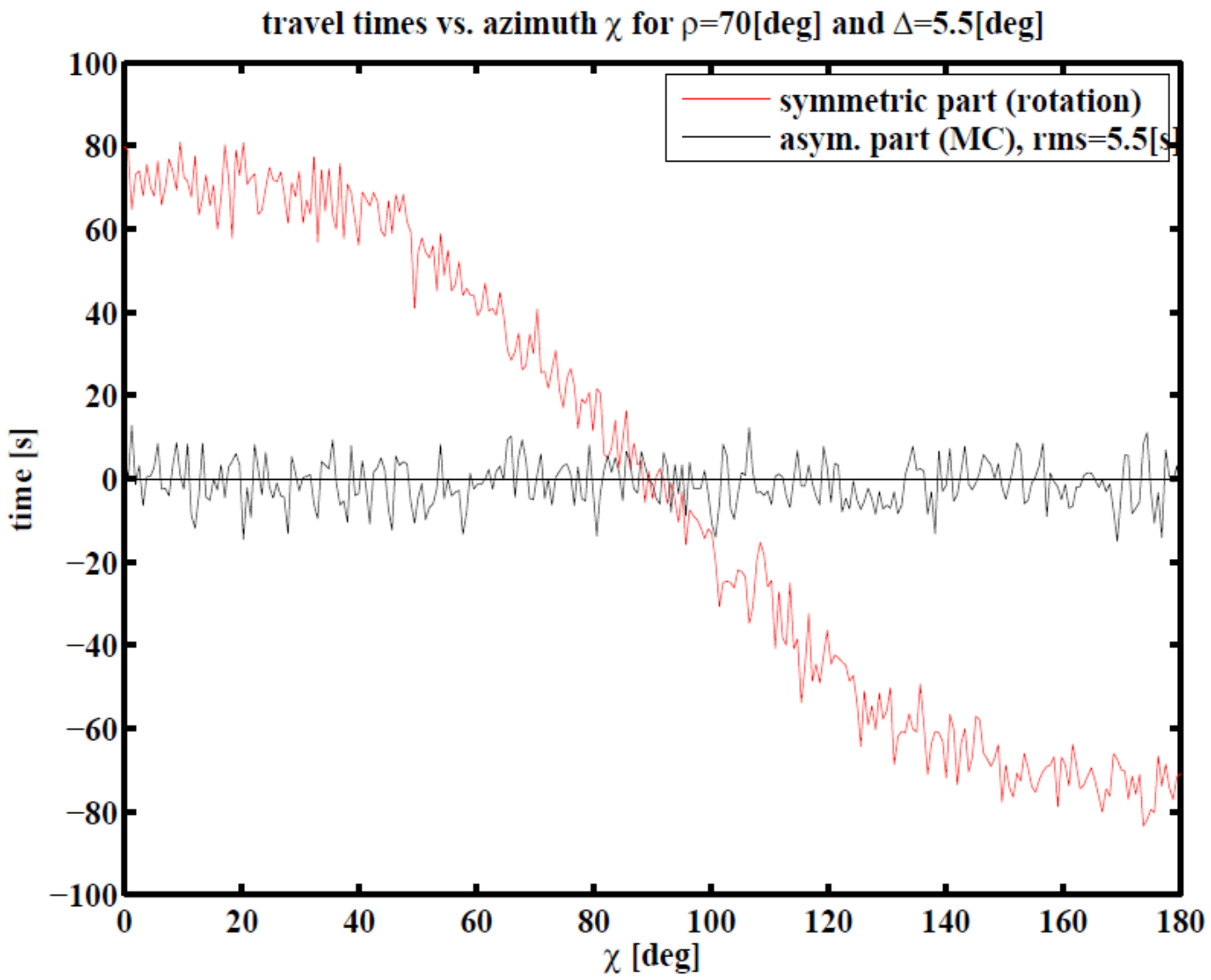
Analysis steps:

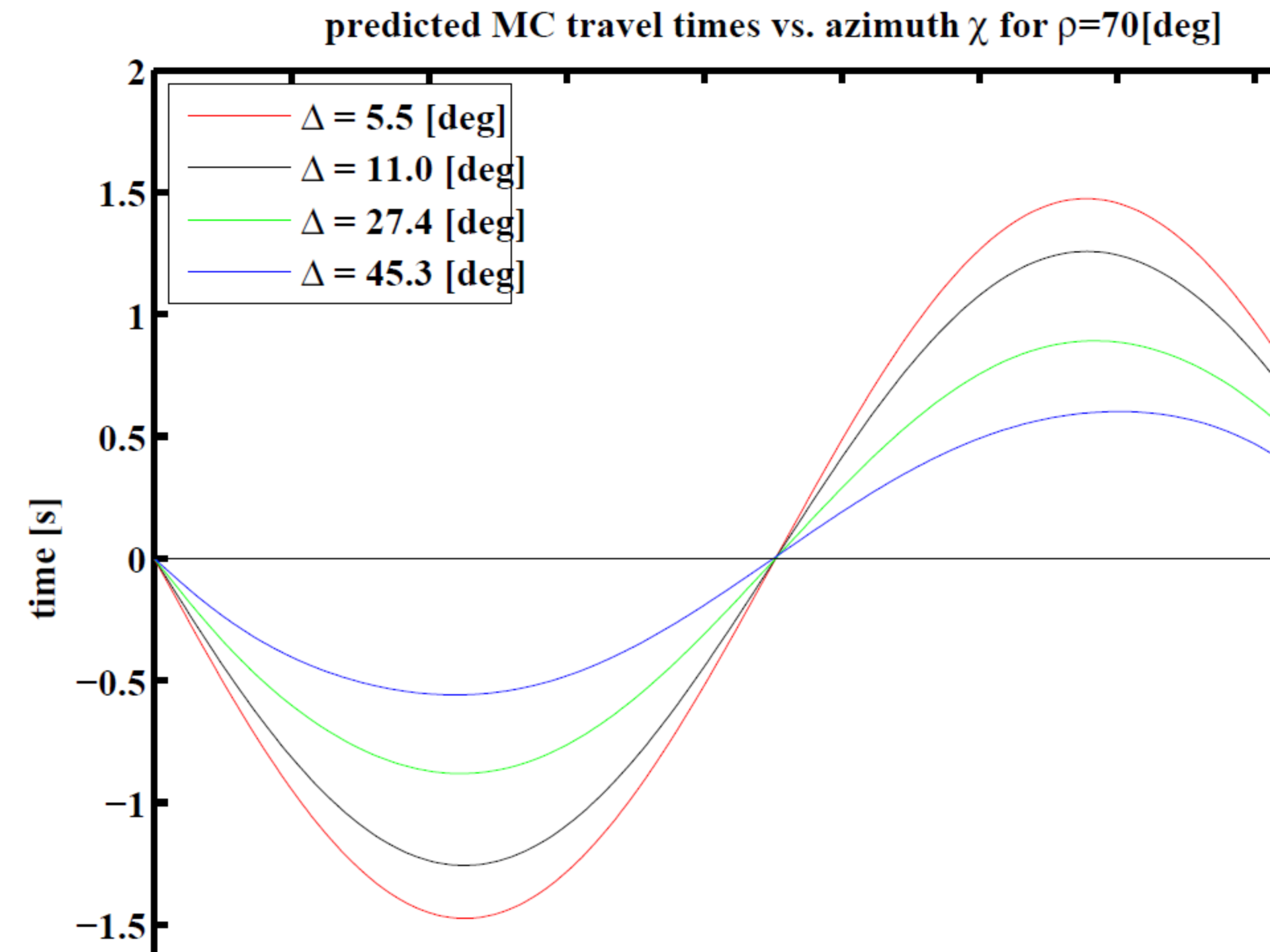
- 1) each HMI image is put onto a longitude-sin(latitude) cooordinate system (Tim)
- 2) Spherical harmonics computed for l<=300 (Tim)
- 3) Images reconstructed on azimuth-heliocentric angle coordinate system for 1 year. This involves putting b0 back in. (Tom, Deep, Tim, Shukur)
- 4) Filtering is done only as a 1st difference in time. (Tom)
- 5) Cross correlations for each day for different lags in azimuth and at the different heliocentric angles separately.
- 6) Average correlations over 1 year.
- 7) Travel times computed using the Gizon-Birch method. A separate reference cross correlation is computed for each heliocentric angle.
- 8) Travel time differences are computed for oppositely directed waves.
- 9) Symmetric and antisymmetric components about the central meridian to separate rotation and meridional circulation.

Polynomial fit to travel time vs. azimuth



Symmetric and antisymmetric parts (across central meridian)




predicted MC travel times vs. azimuth χ for ρ=70[deg]
Δ = 5.5 [deg]
Δ = 11.0 [deg]
Δ = 27.4 [deg]
Δ = 45.3 [deg]
time [s]
2
1.5
1
0.5
0
−0.5
−1
−1.5

Summary

- Big question: is there sufficient s/n to make progress? Not sure.
- Big question: have we really gotten away from center-to-limb systematic errors? Don’t know yet.