helioseismic holography of solar subsurface flows: progress & prospects

Doug Braun

NWRA / CoRA

NorthWest Research Associates

Colorado Research Associates Division
with input from:

A. Birch

C. Lindsey

NWRA / CoRA
outline

“calibrated” (near-surface) flows CR1988
  - supergranulation
  - AR flows (see Braun, et al. 2004 GONG/SOHO 14)

AR flows vs. depth: travel-time asymmetries

inversions
  - zonal and meridional flows

what’s needed?
phase-sensitive holography of flows

egressions and ingressions in 4 quadrants:

\[ H_{\pm}^{E,W,N,S}(r,z,\nu) = \int_{E,W,N,S} d^2 r' G_{\pm}(r,r',z,\nu) \psi(r',\nu) \]

e.g. E-W correlation phase:

\[ C^{E \rightarrow W} \equiv H^E_+ H^W_- \]

\[ \phi^{E \rightarrow W} = \arg \left( \langle C^{E \rightarrow W} \rangle_{\Delta \nu} \right) \]
“calibrated” near surface flows

- assume velocity proportional to phase differences
- will show results for focus=3Mm, calibrated from difference between two tracking rates
- actual averaging kernel for 3 Mm focus:

\[ V_x \propto -\frac{1}{2} \left( \phi^{E\rightarrow W} - \phi^{W\rightarrow E} \right), \text{ etc.} \]
supergranulation:

horizontal divergence

vertical vorticity

27-hr time averages
vertical vorticity of SG as a result of Coriolis force on divergence:

confirms time-distance f-mode results of Duvall & Gizon (2000)
power spectra of supergranulation (divergence)


10° latitude strip @ B=0

B = 45°
AR scale flows (CR1988)

SEE Braun, et al.2004 SOHO 14

ARs: faster rotation

ARs with large spots: outflows

all other ARs: inflows

ARs: no net vorticity
spot outflows: comparison with direct Dopplergrams

line-of-sight component of deduced HH calibrated flows (3Mm focus)

average of 28 hours of MDI Dopplergrams.

HH calibrated velocities in outflows at 3Mm focus are roughly one-half the magnitude of values in the photosphere.
horizontal divergence with depth
(smeared 1°)

focus = 3 - 30 Mm

At all depths, “outflow” signatures from sunspots dominate: are these actual deep outflows or due to magnetic effects?
assessing (and subtracting) surface phase asymmetries

focus depth = 3 Mm  5 Mm  7 Mm

horiz. divergence: original

showerglass phases subtracted

see Lindsey & Braun 2005a,b

see Lindsey & Braun 2005a,b
assessing magnetic effects

- subject of major, ongoing research at NWRA/CoRA and elsewhere
- models taking into account both flows and magnetic effects will probably not be in place by HMI launch
- for now, models of flows will retain flexibility of removing phase contributions based on empirical fits to local $\mathbf{B}$ (strength, inclination)
zonal and meridional flows

[Graphs showing zonal and meridional flows across different latitudes for various magnetic field strengths (3 Mm, 5 Mm, 7 Mm, 9.7 Mm, 14 Mm).]
• multi-channel deconvolution algorithm (for 3D case)

• these rotation and meridional inversions are only 1D (depth) and only include horizontal flows

• averaging kernels (from Green’s functions under Born approx.)

• OLA method

• regularization by hand

• solutions for two depths are shown (3Mm and 14 Mm)
zonal data and inversions

- 3 Mm
- 14 Mm
inversion results

zonal

meridional

3 Mm

14 Mm

Braun AIA/HMI Feb 2006
HH code development needed for flows

- fix foreshortening & near-limb problems
- spherical coordinates
- inversions
  - f mode
  - higher frequencies
larger (science-related) issues to address:

- travel-time asymmetries in magnetic regions
  - understanding physics
  - extracting flow signatures from other effects
- vertical flows? directly? assume mass-conservation?
- combining or using surface flows in inversions, models
- combining other measurements (TD, RD, etc.) in modeling
further information:

http://cora.nwra.com/~dbraun

support:

NASA (LWS and SR&T programs)

NSF (Stellar Astronomy and Astrophysics program)