Time-Distance Inversions of Two Realistic Sunspot Simulations

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Motivation

• TD used often in the past to recover flows QS and around sunspots

• QS TD results promising in upper ~3-5 Mm
  - Lots of uncertainty around active regions possessing strong B-fields
  - Not really any general consensus about subsurface structure of sunspots (shallow, deep? flow structure?)

• Goal to shed light on the validity of current TD methods around active regions
  - Ultimately have confidence in real Sun - tough without validation
  - Comparisons between methods can be useful, but if both are wrong (active regions), it doesn’t help
  - Use realistic MHD simulations for which we know the real flow structure

• Disclaimer: We don’t expect to accurately recover flows near spots - show for completeness

• Filtering, tt’s, kerns, etc. (recent pub, QS analysis is same)
Sunspot Data

- Use two sims (LRes, HRes)
- Provided by M. Rempel (Rempel 2009 a,b)
- Each is ~98x98x18 Mm
- HRes. of 48x48x24 km
- LRes. of 128x128x48 km
- HRes formed and maintained a penumbra, LRes had no penumbra (“pore”)
- Both contain large-scale flow structures away from spot (Fig, time avg’d vx) - vel’s high
- Surface gravity and acoustic waves
Data Filtering

- Doppler time series at tau = 0.01 layer (45 sec) spanning 25 hr.
- Filter out waves whose travel times we would like to measure
- Tested two filter types: phase-speed (common phase-speed and ~depth) and ridge (common radial order) (Fig)
- Ridge filters f-p3 centered on solid black
- First five ps filters from Couvidat et al. (2006) (td1-td5) dashed red
- Power turns up (bound. effect reflections) - Above 12 Mm (40 km/s) dash-dot line
- Filters applied by a multiplication in the Fourier domain
Travel Times

  - GB02 and GB04
  - GB04 linearized version of GB02 (xcorr phase and amp)
  - Trivial to compute

- Travel times measured in the center-to-annulus and quadrant configurations
  - out-in (oi), west-east (we), north-south (ns) (Fig, Δ inc. left to right)

- GB02: ttoi ± changes with filter type and measurement Δ
  - Δ change also seen by Braun & Birch (2008), Couvidat (2012)
  - GB04 almost uniformly positive for both sims (inflow)
Travel Times

- The two definitions agree pretty well away from spots (Fig 1)
- Correlate GB02 & GB04 tt’s for all filters and distances (Fig 2)
- Then apply circular mask of radius 25 Mm and correlate again (Fig)
  - Past 25 Mm, GB02 and GB04 show good correlation (>0.98)
Forward-Modeled tt’s

- Kernels in Born: computation of kernels depends on accurate modeling of simulation power spectra
  - Find QS and spot simulation power spectra identical in the sense that they matched the model power equally well
  - And we don’t account for B-field in kernel computation

- Simulated data allows us to test kernel performance through forward modeling
  - Convolution between kernels and actual simulation flow fields

- If kerns perfect and no tt noise, FM should match measured tt’s perfectly
  - Always some level of noise, don’t account for B-field (might expect significant mismatch)

- FM of tt’s computed and correlated with measured ones (Fig, masked)
  - High corr., but bad corr. for p3 and td5 (same as QS)
SOLA LRes vh Inversions

- Quick - can use the already-computed QS weights (same kernels and travel-time noise)

- (Fig) Each row shows flow maps recovered by inverting diff. set of GB02 tt’s

- Each column is a diff. depth
  - Bottom row are sim. flow maps

- 1 Mm - Capture much of the overall flow structure away from spot (flows only effected in umbra)

- 3 Mm - Some struct. still visible, but surrounding flows washed out by large flows in umbra

- 5 Mm - Sign change around spot (outflow now)

- None of this flow structure is visible in the actual simulation
HRes vh Inversion Results

Both GB02 and GB04 shown here

1 Mm  3 Mm  5 Mm

HRes see moat flow - Hard to tell both do okay away from spot

GB02 gets moat flow (not GB04), inflow seen in umbra
HRes Correlations

- I said they agree well outside of the spots - mask and correlate inv’s and answer (Fig)
  - Filter type is given by line color, but don’t worry about that now
  - Solid lines are GB02 and dashed are GB04 (agree well in upper 3 Mm)
  - Inverted forward-modeled correlations are very high (kind of weird?)
Spot Conclusions

• Able to recover flow structure in upper 3 Mm, but only at sufficiently large distances from these magnetic features (~30 Mm)

• Consistently underestimate flow amplitudes (like quiet Sun sims)
  - Could be non-linearities due to strong flows? (many >500 m/s)

• No single “best” filtering scheme
  - Ridge, ps, comb filtering
  - ps and comb give comparable results, ridge worst

• Inversions of GB02 tt’s are more robust (suggested before)

• Inversions of forward-modeled tt’s outperform those of measured tt’s in terms of horizontal flow correlations
  - Probably highlights our inability to accurately measure travel times around strong magnetic features
Sensitivity Kernels

- Need to relate surface $t_t$ measurements to subsurface conditions present in simulations
  \[ \delta \tau^a(r) = h_x h_y \sum_{ij} K^a(r_i - r, z_j) \cdot \nu(r_i, z_j) + \mathcal{N}^a(r) \]

- Represent the sensitivity of wave travel times to flows
  - Assumes $t_t$'s vary linearly with the subsurface perturbation

- This is a linear relationship between $t_t$'s and flows
  - One set per filter, per $\Delta$ (Fig, hor. avg.)

- Set of kernels in Born approximation (Birch 2007)
  - Significant consequences

- Note: B-field perturbations not accounted for in kernel computation

Figure 5.— Horizontally integrated 'we' sensitivity kernels as a function of depth. The top panel shows examples of kernels for ridge filters and the bottom panel shows those for phase-speed filters. In each case, the absolute value is shown, and each profile has been normalized by the largest sensitivity value in that particular plot. The kernel distances for which these are computed correspond to the mid-range value for each filter.
A major goal in solar physics is to understand the subsurface structure of sunspots, as they are a dominant feature at the solar surface.

Despite abundant surface observations, there is no general consensus about their subsurface properties.

Helioseismic results regarding spot structure are often mixed regarding depth (shallow, deep?) and flow structure.

Goal: use two of the most realistic spot simulations we have available to us to test performance of TD helioseismic methods (flows).

Disclaimer: We don’t expect to accurately recover flows near spot (see what happens).

Identical to QS in terms of filtering, kernels, tt’s, inversions (weights).
Travel Times

- Illustrate comparison another way: Azim-avg oi tt’s around spot center rad profile (Fig)
- Dashed lines are boundaries of umb., pen., 25 Mm mask
- Inset plots >25 Mm
- Effect of B-field evident near spot (sign diff. between GB02 and GB04)
- Agreement at 25-30Mm, then small values
HRes Correlations

- I said they agree well outside of the spots - mask and correlate inv’s and answer (Fig 1)
  - Filter type is given by line color, but don’t worry about that now
  - Solid lines are GB02 and Dashed are GB04 (agree well in upper 3 Mm)
  - Inverted forward-modeled correlations are very high (kind of weird?)

- Another test: correlate annuli of increasing radii (but same area) (Fig 2)
  - See how corr. changes with distance from spot center
  - Solid lines are GB02 and dashed are GB04
  - Find agreement after ~30 Mm
Quiet Sun Helioseismology

• Before jumping in to the active regions, first validate using quiet-Sun simulations - if promising, then go on to more complicated

• Couple of previous QS validation studies: Zhao et al. (2007) inversions in ray approximation of convective sims by Benson et al.
  - Good horizontal flow correlation, but bad vertical

• Svanda et al. (2011) invert FM travel times
  - Good horizontal and improved vertical flow correlations
  - Implemented regularization parameters to minimize x-talk

• How do our inversions compare?

• Some detail about data filtering, tt’s, kerns, etc. (sunspot analysis is same)
QS-Simulations

- Use two QS-sims (QS1, QS2) - 20 hrs
- Provided by M. Rempel (Rempel 2009 a,b)
- Each is ~98x98x18 Mm
  - QS1 64x64x32 km
  - QS2 128x128x48 km (Fig, vx)
- Periodic boundary conditions, and both are magnetic
- Both contain large-scale supergranule-sized flows (fast) which extend deeply through domains
- Surface gravity and acoustic waves
Travel Times

- Wave travel times measured by finding the difference between measured cross-covariances between pairs of points and a reference cross-covariance function.


- Travel times measured in the center-to-annulus and quadrant configurations.

- Measured over 11-29 Mm inc. of 4 Mm.

- One tt-map per distance, per filter (117 measurements) (Fig, large flows).

- Corr > 0.99, GB04 10% larger.

GB04 ttoi QS1, QS2, p2 (L), td3 (R)
Sensitivity Kernels

• Need to relate surface tt measurements to subsurface conditions present in simulations

• Represent the sensitivity of wave travel times to flows

\[ \delta \tau^a(r) = h_r h_z \sum_{ij} K^a(r_i - r, z_j) \cdot v(r_i, z_j) + N^a(r) \]

• This is a linear relationship between tt perturbation and flows

• Set of kernels in Born approximation (Fig, hor. avg.)

• Can compute FM tt’s by convolving kernels and sim flows - compare to measured ones

• High corr. between meas. and modeled tt’s, except p3 and td5 (modeling issue?) (Fig)
SOLA Inversions (vh) QS2

1 Mm  3 Mm  5 Mm

noise = 35 m/s

- Each row inv’s by inverting diff. set of tt’s
- Each column is a diff. depth
- Results reliable in upper 3 Mm
  - Corrs. 0.9, 0.8, 0.6
- Underestimate flow vel’s by 50%
- ps slightly better, ridge is the worst
QS2 vz Inversions

- Implemented weight and x-talk constraints Svanda et al. (2011) (Fig)
- Phase-speed: QS2 okay at 1 Mm, all others very bad
- QS1 bad at all depths

ps inversions best cols: 1, 3, 5 Mm
Fig. 14.— Correlations between the QS2 flows at 1 Mm depth and those at deeper layers. The dashed lines are for the inferred flows from the inversions ($v_{\text{inv}}$), and the solid lines are directly from the simulation ($v_{\text{tgt}}$). Each case shows the mean correlation found using the individual flow components $v_x$ and $v_y$, as well as the correlation found using the horizontal divergence, $r_h \cdot v_h$. 
A major goal in solar physics is to understand the subsurface structure of sunspots, as they are a dominant feature at the solar surface.

Despite abundant surface observations, there is no general consensus about their subsurface properties:
- Mechanism of formation
- How they are assembled and transported through the convections zone
- What their 3D subsurface structure is

They are of particular importance as they are a product of the solar dynamo, and are associated with energetic solar events like flares and coronal mass ejections.

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Identical to QS in terms of filtering, kernels, tt’s, inversions (weights)
10) Quick QS Conclusions

- Horizontal inversion results correlate well with simulation flow maps in upper 3 Mm of domains (0.8-0.9), but worse deeper.

- We consistently underestimate flow amplitudes
  - Possibly suggests some non-linearity of the forward problem due to strong flows in the sims (>500 m/s).

- Phase-speed filtering scheme slightly outperformed the others in terms of flow correlations in the upper 5 Mm.

- Vertical inversions show very poor correlation with simulation flow maps at nearly every depth.
Fig. 12.— Azimuthally-averaged radial velocity profiles computed from the $v_{inv}^{x,y}$ flow maps for LRes (top row) and HRes (bottom row) at depths (left to right) 1, 3 and 5 Mm. Results obtained using both GB02 and GB04 travel-time definitions are shown together in the same figures. The solid black lines correspond to the azimuthally-averaged radial velocity computed from the smoothed simulation flow maps (i.e. $v_{tgt}^{x,y}$) at each depth. All profiles have been normalized by the largest absolute velocity value of the simulation profile in each figure for easier comparison. The gray dashed lines represent the magnetic field profile (i.e. $|B| = B_x^2 + B_y^2 + B_z^2$) and the depth corresponding to the right-most y-axis in units of Gauss. The vertical dashed lines represent the boundaries of the simulation umbra, penumbra, and the circular mask.