Local helioseismology: methods and challenges

Doug Braun

contributions from

A. Birch (MPS),

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M. Rempel, Y. Fan (NCAR)

NWRA
Since 1984

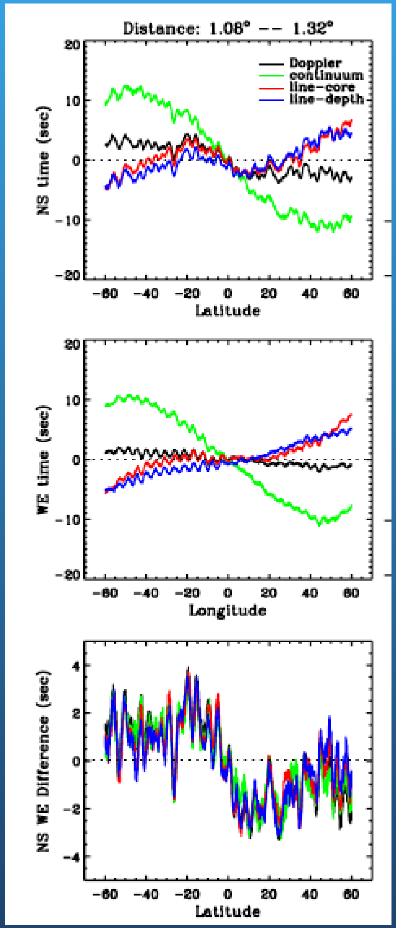
outline

- meeting the challenges of random and systematic errors with use of numerical simulations, ensemble averaging
  - Example 1: center-to-limb “flow” artifacts
  - Example 2: wave scattering by small magnetic elements
  - Example 3: helioseismic precursors to emerging ARs
  - Example 4: modeling subsurface structure of sunspots

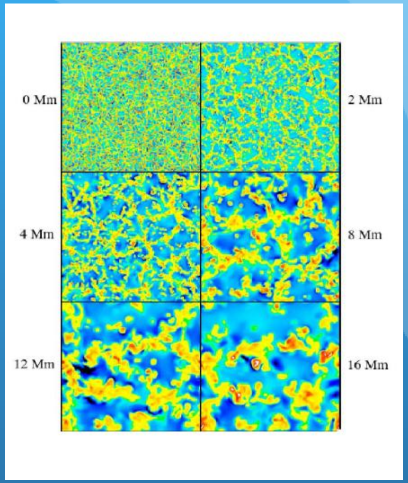
Example 1: (systematic effects) the "shrinking/expanding" sun

- Use of numerical simulations to understand center-to-limb "flow" artifacts (e.g. Zhao et al 2011)
- asymmetries in solar convection (e.g Stein et al. 2009) lead to phase shift whch vary with height
- See Baldner & Schou (2012, ApJ)

Zhao et al 2011



Stein et al 2009



Baldner & Schou 2012

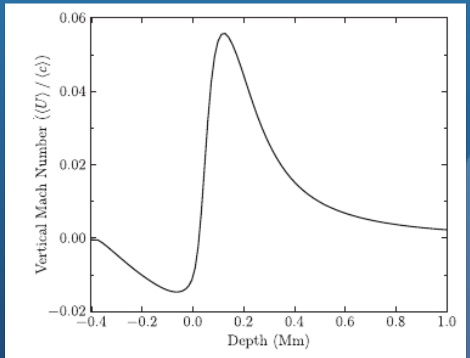
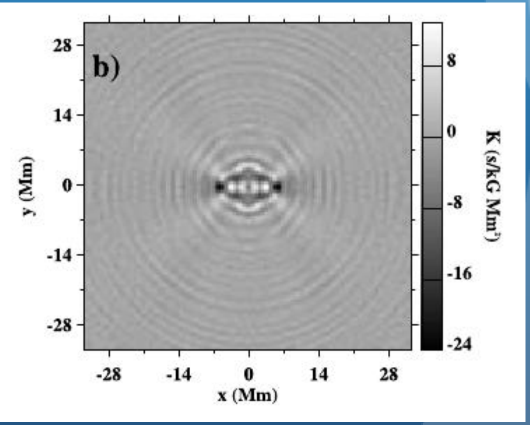


Figure 1. Mach number as a function of depth from a model by Stein et al. (2009). The area average of the flow divided by the area average of the sound speed is used. To exclude the buffer zone used in the model the outer 5 grid points were excluded. The Mach number below 1 Mm is negligible.

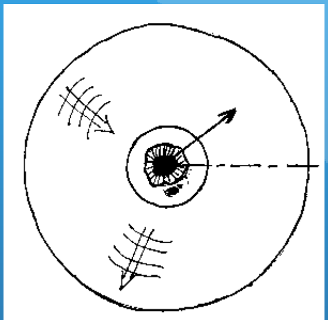
ensemble averaging (prior usage)

- combines measurements to facilitate analysis of “average” (noisy) feature
- empirical time-distance kernels from travel-time maps of small magnetic elements
  - Duvall, Birch & Gizon (2006)
- vertical flows of supergranulation
  - Duvall & Birch (2010)
  - Švanda (2012)



Example 2: (noise) wave scattering of small magnetic elements

- Use of ensemble averaging to measure scattering (Hankel analysis) of small magnetic elements
- Use of numerical simulations to model interaction of f-modes with magnetic flux tube
- See Felipe, Braun, Crouch, & Birch (2012, ApJ)



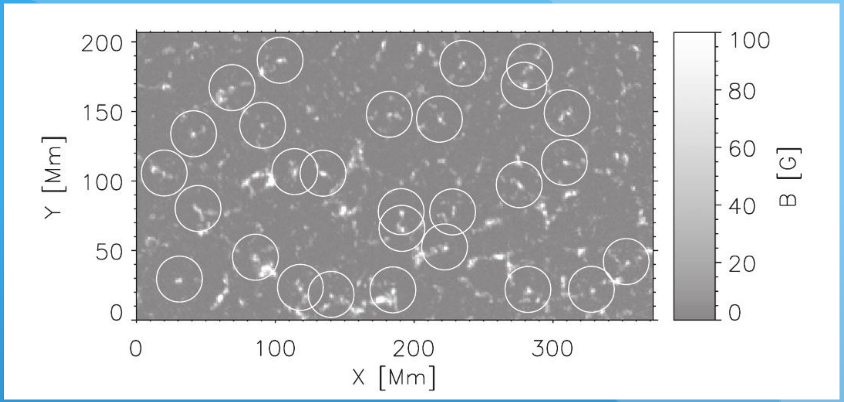
$$\Psi_m(\theta, \phi, t) = e^{i(m\phi + 2\pi \nu t)} \times \left[A_m(L, \nu) H_m^{(1)}(L\theta) + B_m(L, \nu) H_m^{(2)}(L\theta)\right]$$

Felipe, Braun, Crouch and Birch 2012 *ApJ*

- ensemble averaging of BA^*

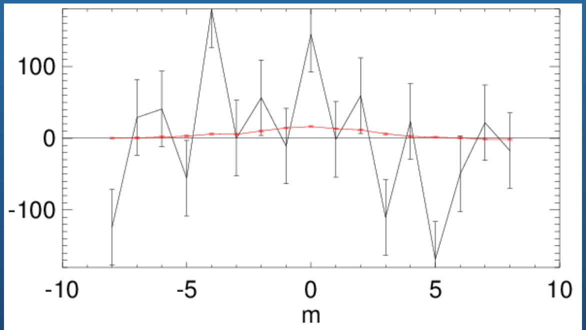
$$\langle B_m A_m^* \rangle'_{\mathrm{me}} = |\langle B_m A_m^* \rangle_{\mathrm{me}}| e^{i[\arg(\langle B_m A_m^* \rangle_{\mathrm{me}}) - \arg(\langle B_m A_m^* \rangle_{\mathrm{qs}})]},$$

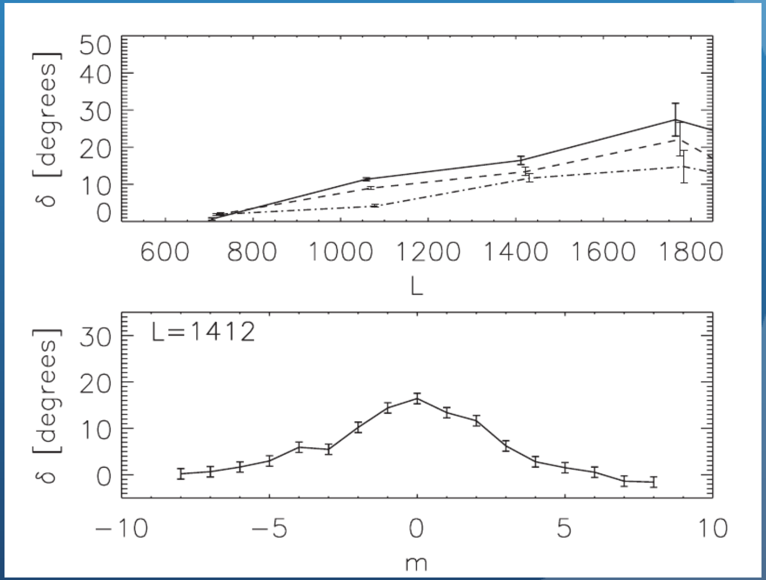
$$\delta_{\mathrm{obs}}(L) = \arg\left(\int_{\nu_0(L)-\delta\nu}^{\nu_0(L)+\delta\nu} \langle B_m(L,\nu) A_m^*(L,\nu) \rangle'_{\mathrm{me}} d\nu \right)$$



analysis of 3400 elements!

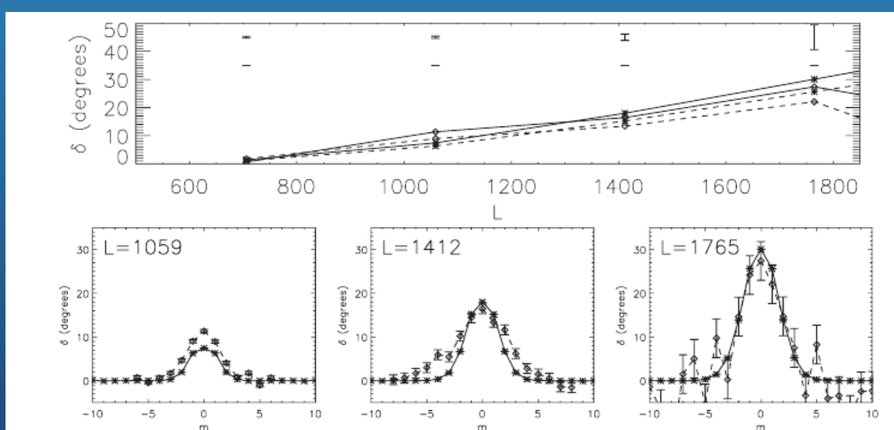
analysis of single magnetic element!

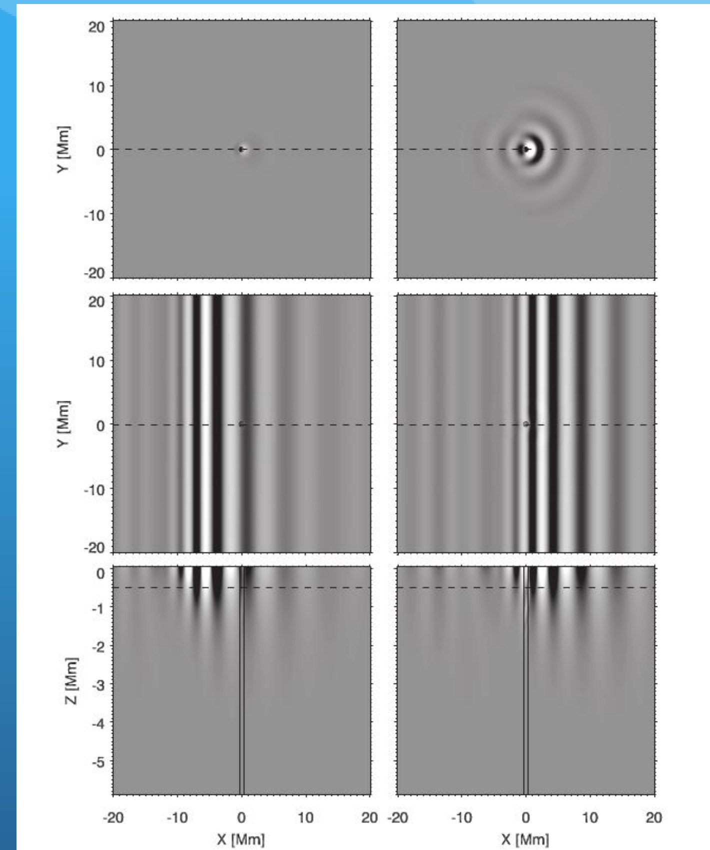


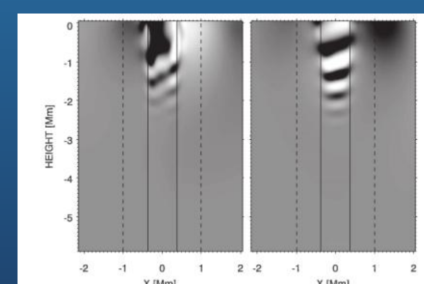


Felipe, *et al* 2012 *ApJ*

- numerical propagation of f-mode wave packet through magnetic flux tube
- Excitation of tube & jacket modes
- Can reproduce phase shifts; also shows absorption (see paper)



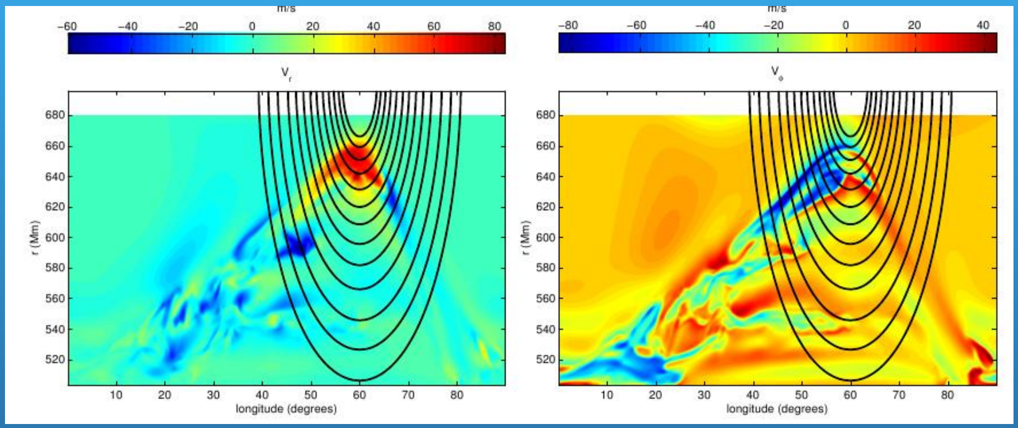




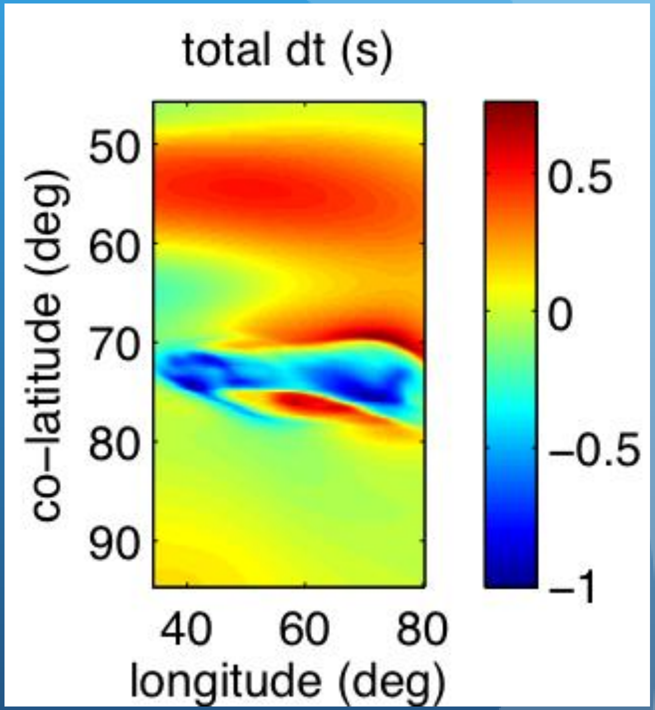
Example 2: search for pre-emergent active region signals

- Use of numerical simulations to predict helioseismic signatures (Fan, Birch & Braun 2010)
    - emerging flux simulations by of Fan (2008)
- Survey of pre-emergent helioseismic signatures (Leka et al; Birch et al 2012 *ApJ* submitted)
    - 107 ARs observed with GONG network for 24 hr prior to emergence; 107 quiet-Sun control sets
    - ensemble averaging over 5x6-hr segments of helioseismic signatures

estimate of detectability of rising flux tubes (Birch, Braun & Fan 2010 *ApJ*)



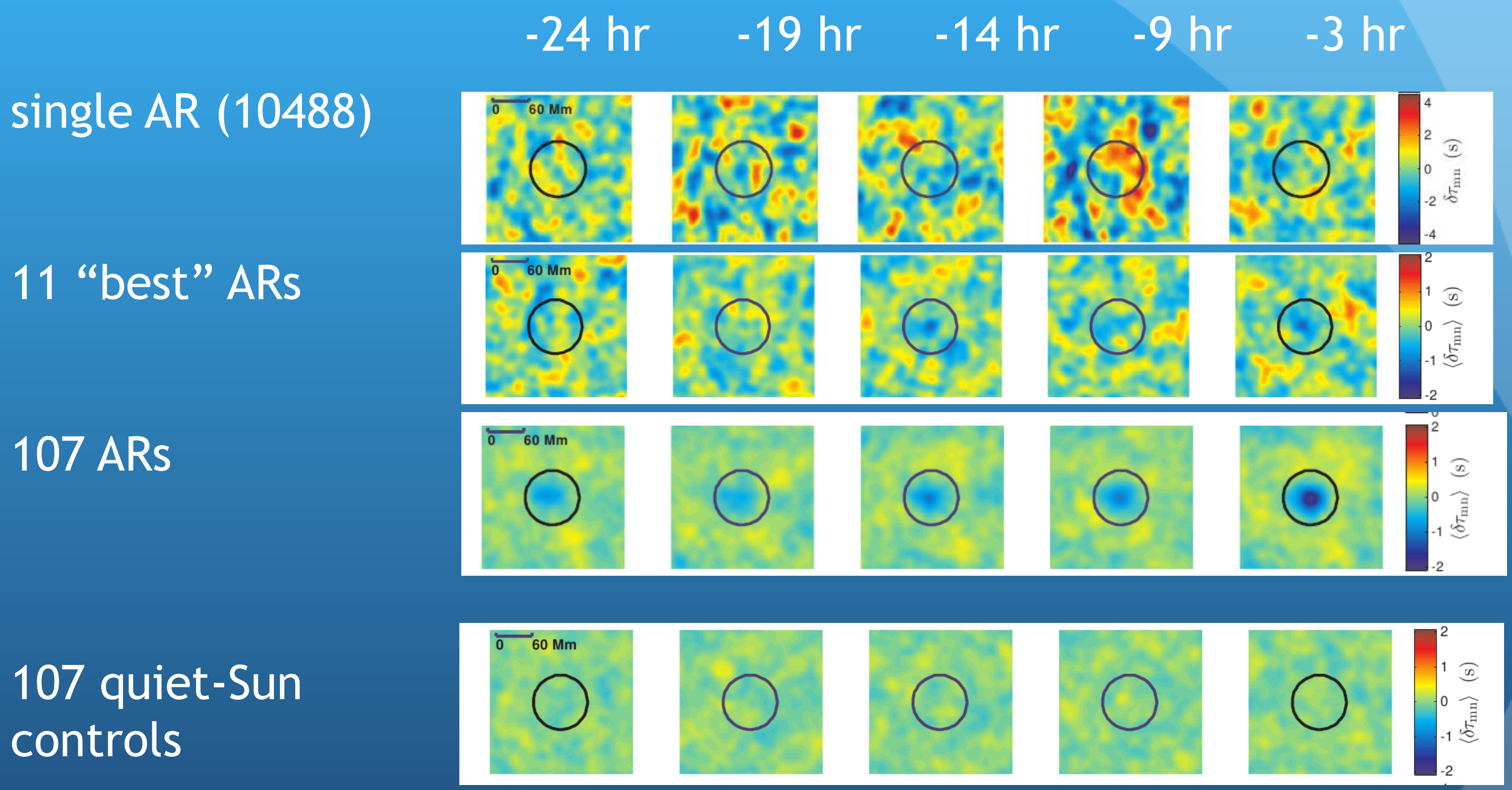
vertical (red=upward) horizontal (blue=retrograde)



- 100 m/s retrograde /upward flow is largest signal
- below noise for single region
- detectable with ensemble averages ~100 ARs

results: mean travel-time shifts

(TD5 filter; depth ~ 0-10 Mm)



Birch et al. 2012 *ApJ* accepted

results: other averages…

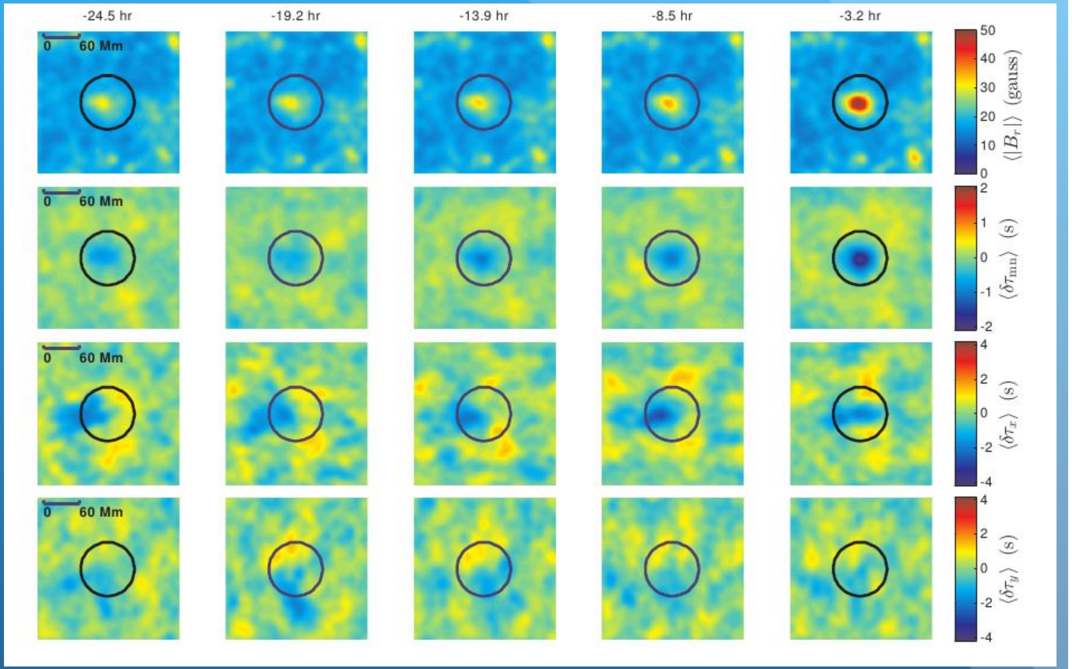
-24 hr -19 hr -14 hr -9 hr -3 hr

mean B

mean travel-time shift

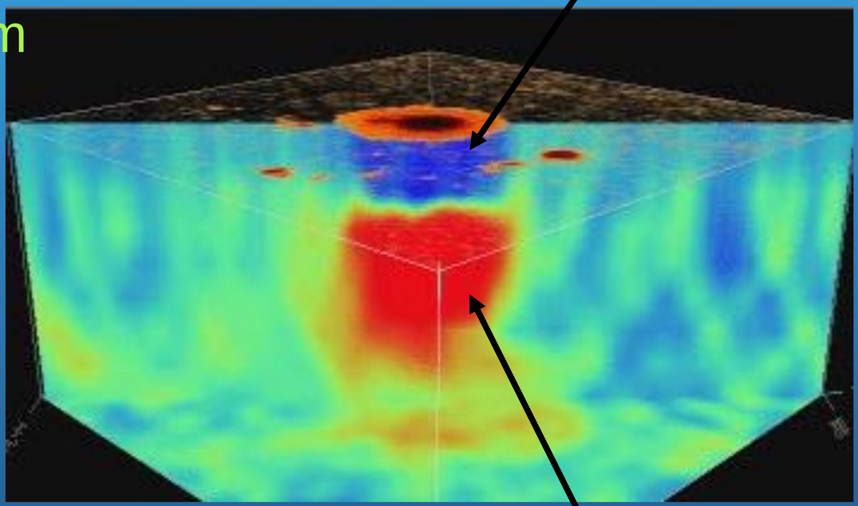
EW travel-time shift

NS travel-time shift



- statistically significant flow & wave-speed signatures preceding emergence:
  - τ_{mean}~ -0.3 sec reduction
  - τ_x ,τ_y~ 2 sec converging flow ~ 15 m/s
- Weak photospheric magnetic signal correlated w/ τ_{mean}
- can rule out spatially extended flows > 15 m/s down to 20 Mm and within prior 24 hr

Example 4: testing "standard" structure inversion in sunspots



ray theory (e.g. Kosovichev, Duvall & Scherrer 2000; Hughes et al 2005)

$$\delta\tau = \int_{\Gamma} ds \frac{k}{\omega} \frac{\delta w}{c}$$

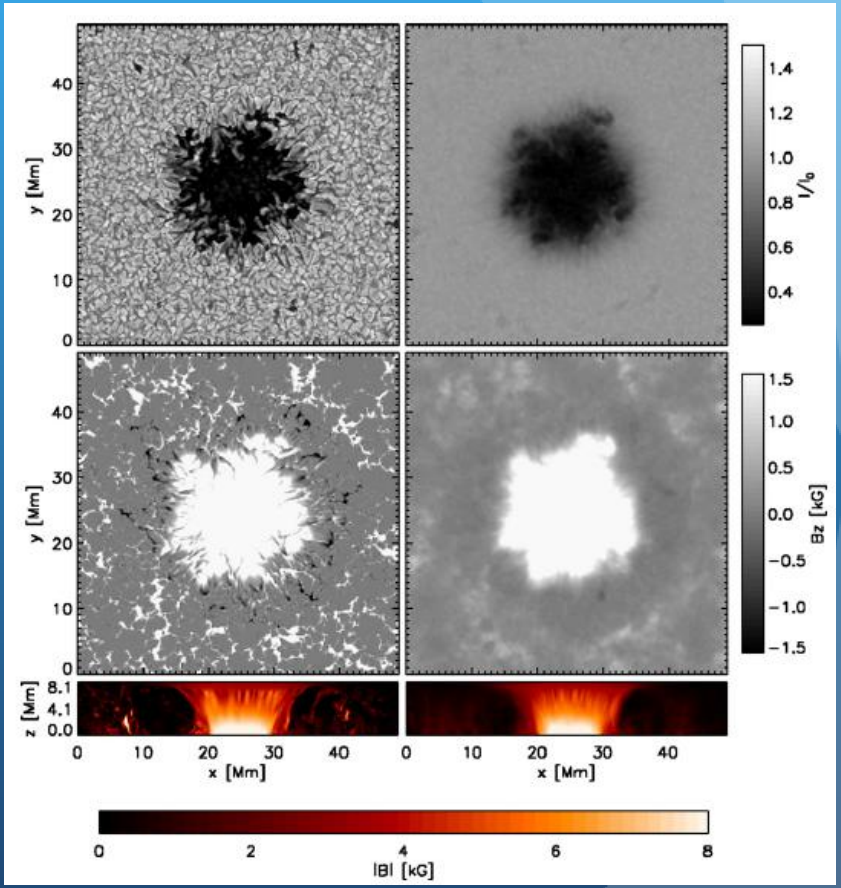
change due to fast-mode or thermal perturb.

Born approx. (e.g. Couvidat et al. 2006)

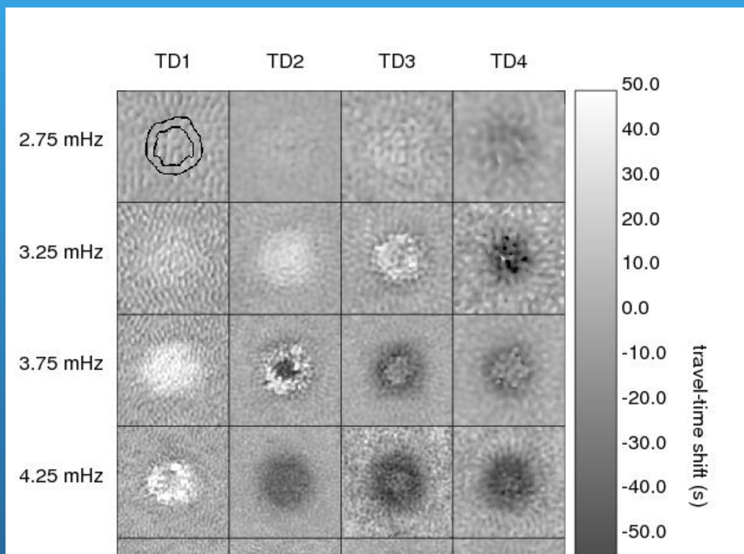
$$\delta\tau = \int_{V} d\mathbf{x} \mathbf{K}(\mathbf{x}) \cdot \frac{\delta w^2}{c^2}(\mathbf{x})$$

numerical data

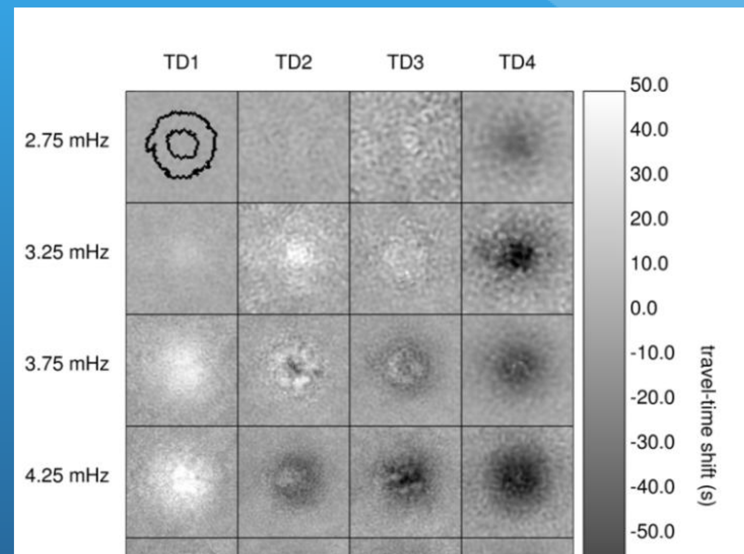
- M. Rempel (HAO/NCAR) magnetoconvection simulation using MuRAM code
- data is publicly available (www.hao.ucar.edu)
- see Braun, Birch, Rempel & Duvall (2012)



Rempel simulation is consistent helioseismically wih real sunspots...



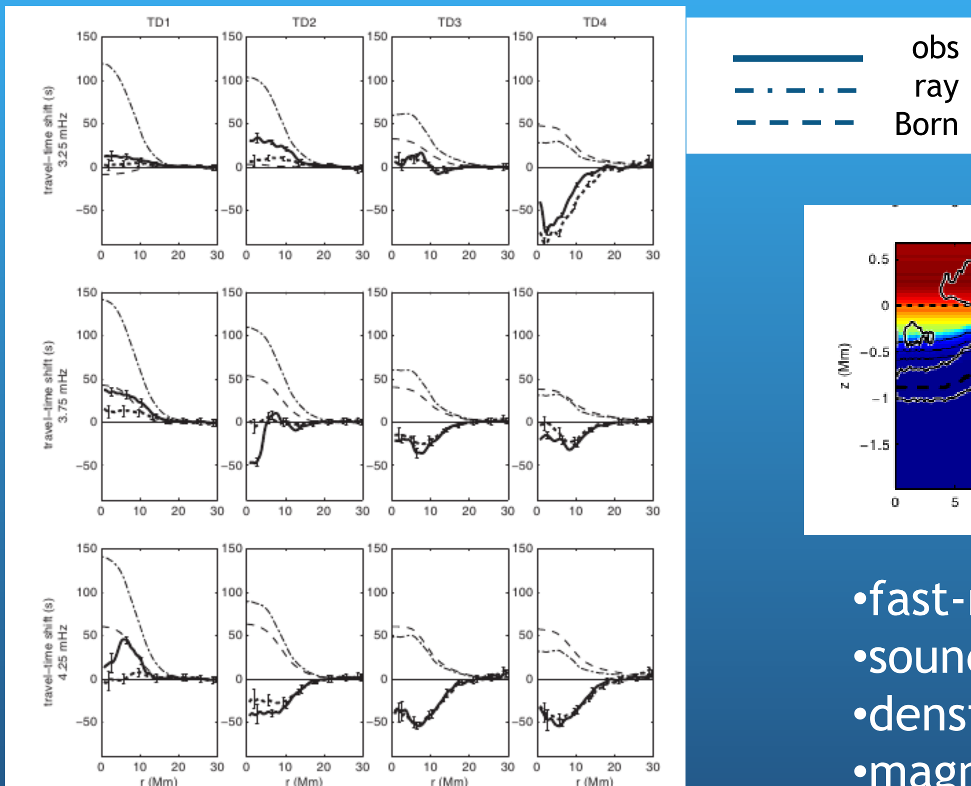
simulation

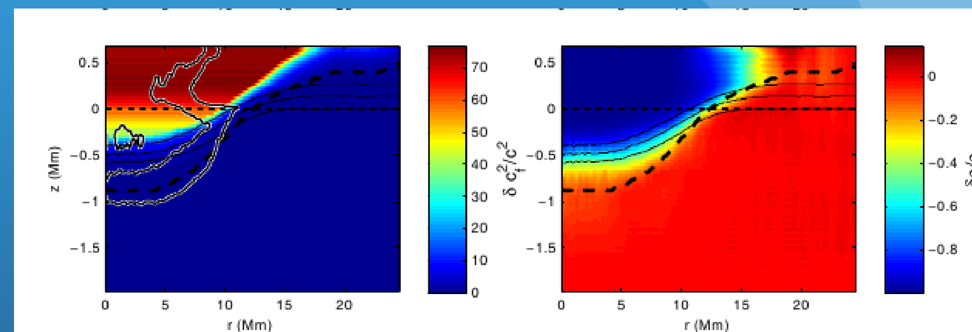


AR11092

Braun, Birch, Rempel & Duvall (2012)

…but standard assumptions do not predict correct travel time shifts





- fast-mode speed perturbation $\delta c_f^2 / c^2 \approx 50$
- sound-speed perturbation $\delta c^2 / c^2 \approx -0.7$
- density perturbation $\delta\rho / \rho \approx -0.8$
- magnetic field $\beta \approx 1$

Braun, Birch, Rempel & Duvall (2012)

sunspot structure inversions; future work

- addressing failure of Born/ray approximations:
  - cookie-cutter tests - eliminate ray paths through surface perturbation
  - invert with respect to magnetostatic model (first guess) – this is computationally very expensive (kernels vary with position)
- ensemble averaging of sunspots
  - helpful to determine if there is a deep perturbation worth seeking
- what about flow inversions?

acknowledgements

- data from: GONG, *MDI/SOHO*, HMI/*SDO*
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  - NASA SDO-Science Center NNH09CE41C (sunspot inversions)
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  - NASA GI NNH09CE43C (small magnetic elements)