Local helioseismology of sunspot regions: comparison of ring-diagram and time-distance results

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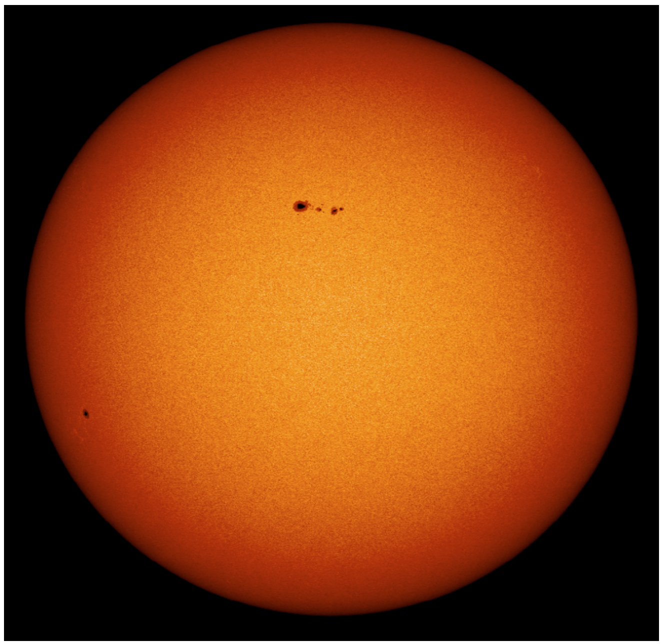
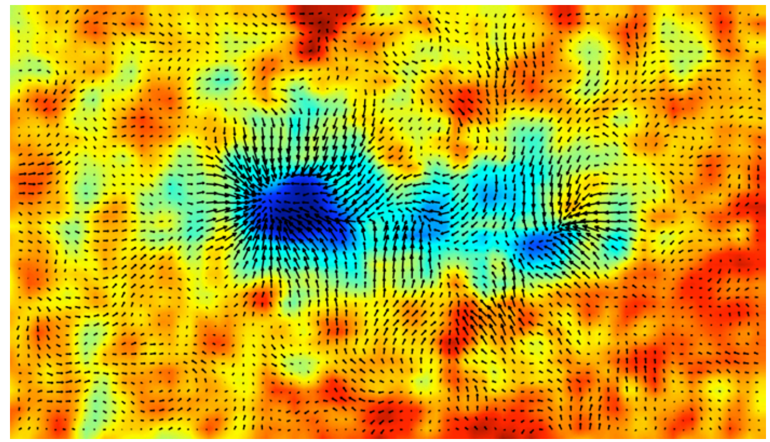
HMI Local Helioseismology (Time-Distance and Ring Diagram) Pipeline

Input:

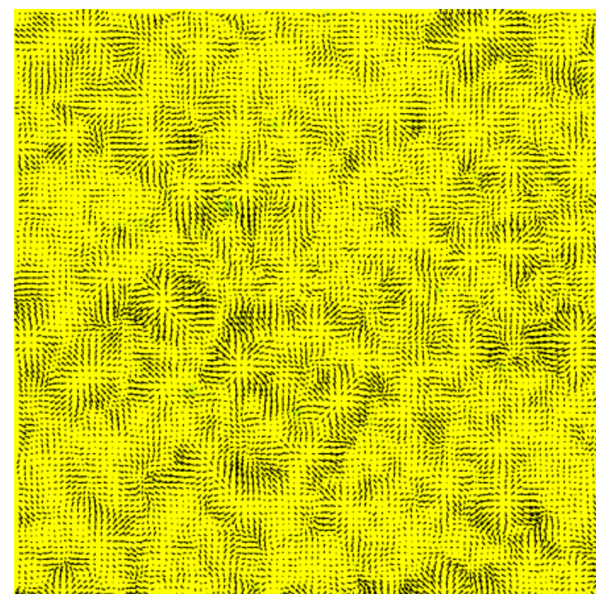


Dopplergrams and intensitygrams

Output: Active region structures and flows



Full-disk and synoptic flow and sound-speed maps



Verification, testing and investigation of systematic effects are crucial for local helioseismology

- **Two approaches of the LoHCO team to testing and verification:**
  - **Comparison of local helioseismology methods**
    - Ring diagram analysis
    - Acoustic holography/imaging
    - Time-distance helioseismology
  - **Testing using numerical MHD simulation data, available for helioseismology**
    - Wave propagation linearized MHD codes
      - Local sunspot regions (K.Parchevsky)
      - Full-Sun sphere (T.Hartlep)
    - Non-linear radiative MHD codes
      - MSU code (R.Stein)
      - NASA/Ames code (A.Wray)
      - MURAM code (M. Rempel)

Example: sound-speed structure below sunspots

Travel-time inversions inferred the sound-speed perturbation beneath sunspots, which is different for different sunspots but typically negative in a shallow subsurface layer and positive in deeper interior

Born kernels   Ray-path kernels

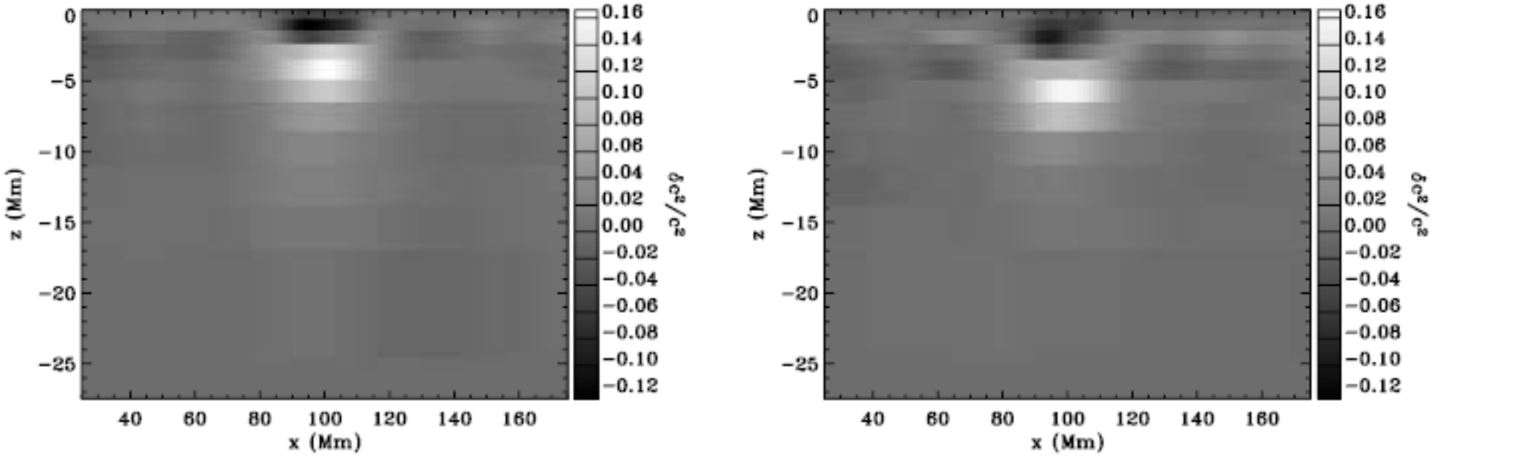
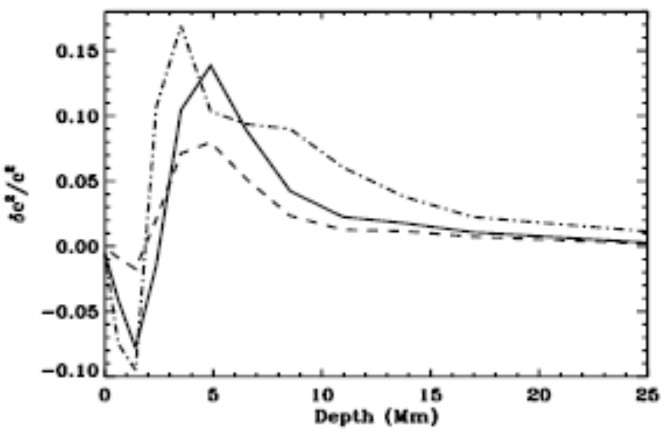


FIG. 4.—Vertical cut in the inversion results around $y = 97$ Mm. *Left*: Inversion using Born approximation kernels. *Right*: Inversion using ray-path kernels.

Couvidat et al (2006)

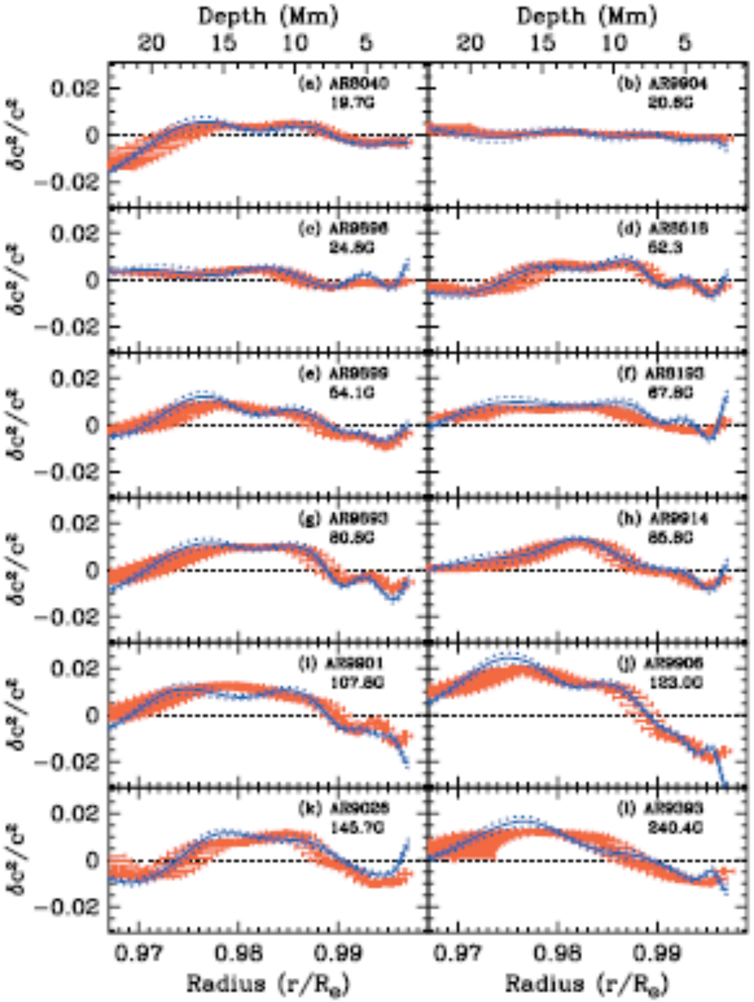


Sound-speed profiles for 3 sunspots

The inferred sound-speed structures depend on variations of temperature, magnetic field, MHD turbulence and other complicated physics of acoustic waves, which is studied by simulations.

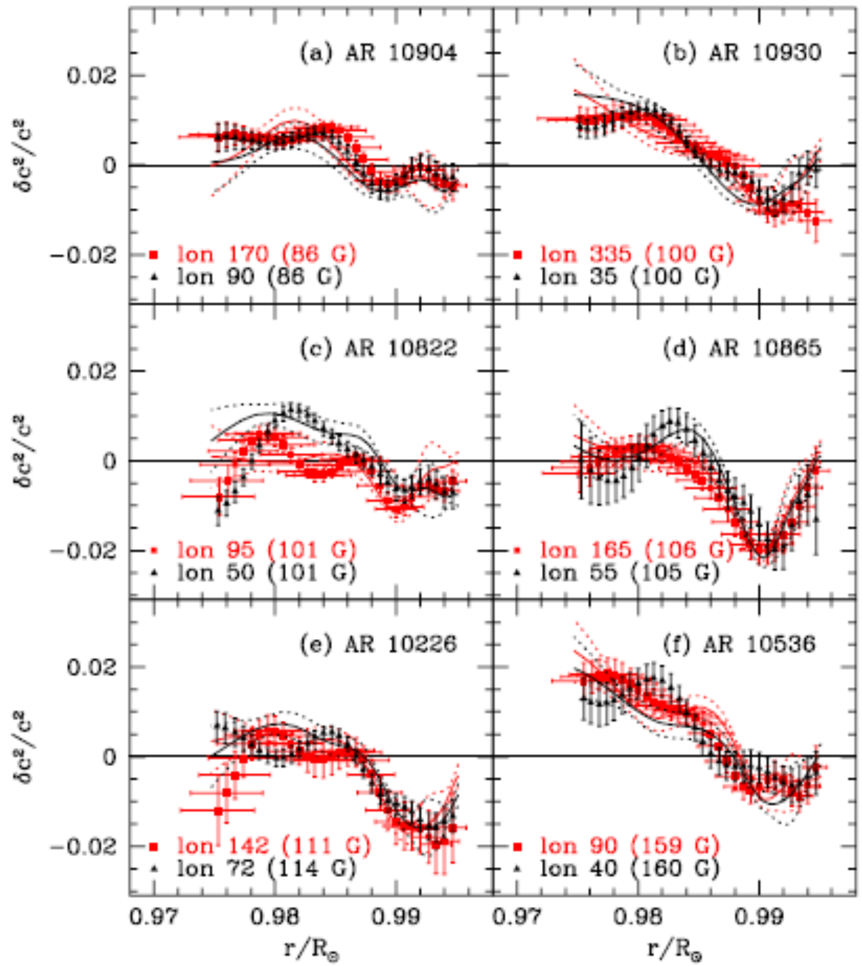
Ring-diagram inversions showed a qualitative agreement with time-distance results

Basu et al (2004)



the sound speed is higher in the active regions. This is consistent with results obtained using the time-distance analysis (Kosovichev et al. 2000, 2001). The lower sound speed in the immediate subsurface layers could be a result of reduced temperature in active regions (Kosovichev et al. 2000). In all cases

Bogart et al (2008)



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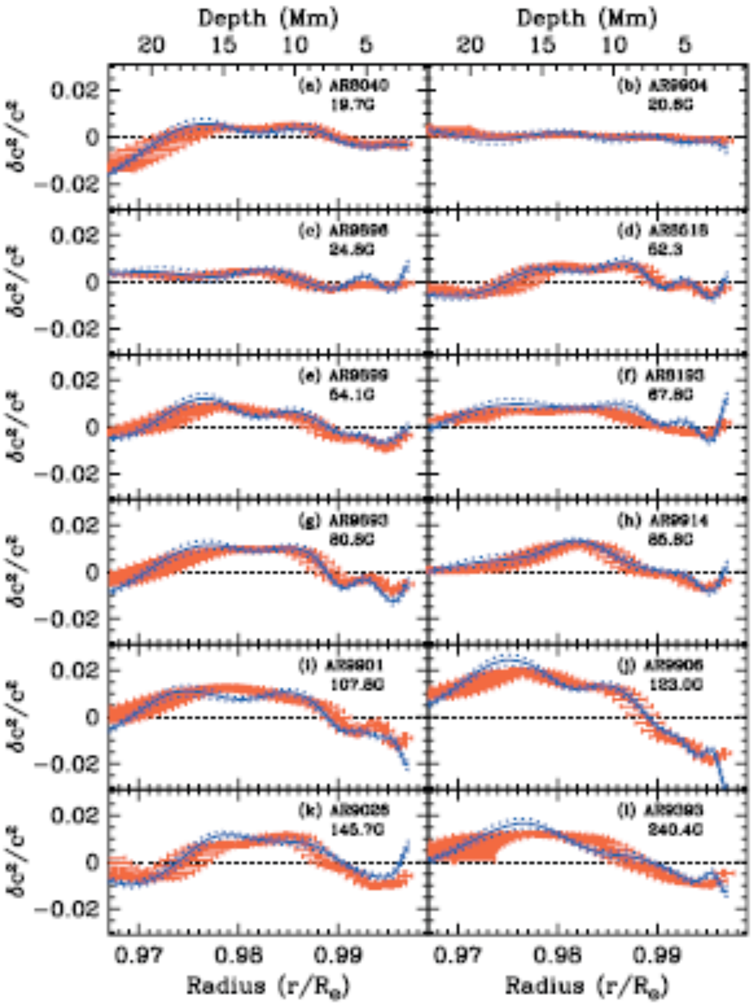
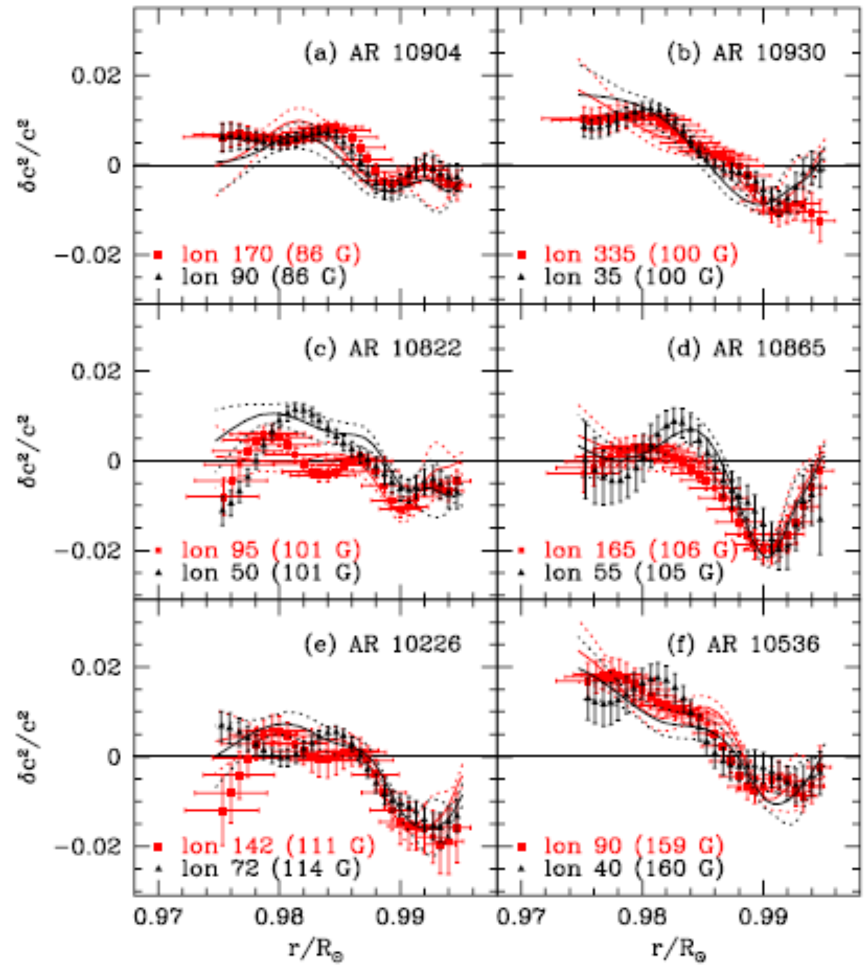
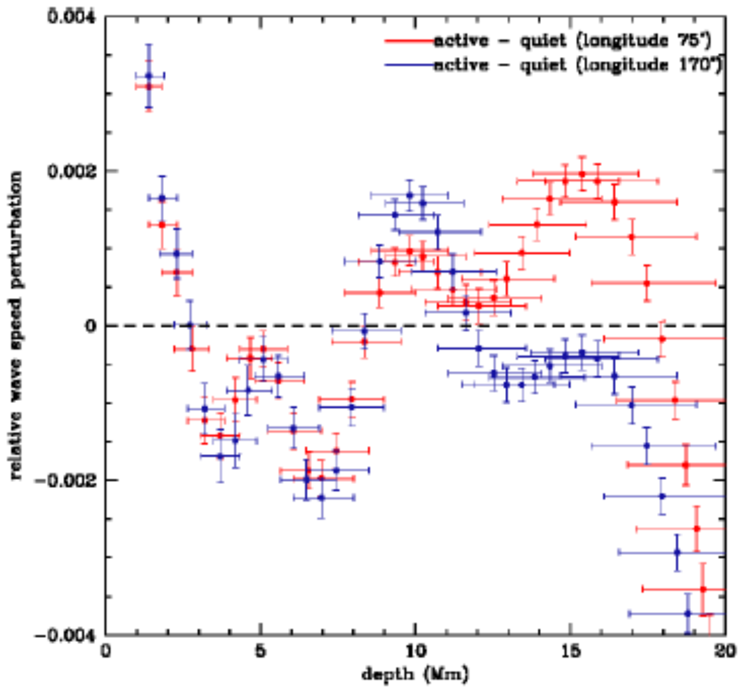


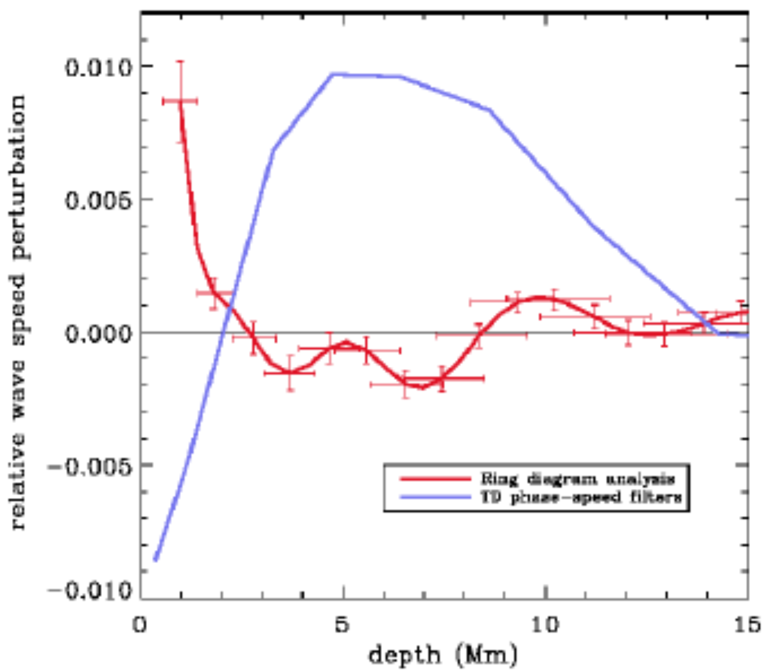
Bogart et al (2008)



The general trend in the results is clear and confirms that of the earlier analysis of MDI data for the few comparatively strong active regions: a region just below the surface with negative sound-speed and adiabatic-index anomalies and a turnover to positive anomalies at greater depths.

However, comparison of ring-diagram and time-distance inversions by Gizon et al (2009) for AR 9787 showed a significant discrepancy, and suggested that the sunspots can be very shallow structures if the ring-diagram results (shown by red curve) are corrects, also in agreement with some sunspot models. Also, it was suggested that both local helioseismology inferences are invalid because perturbations in sunspots are not small.





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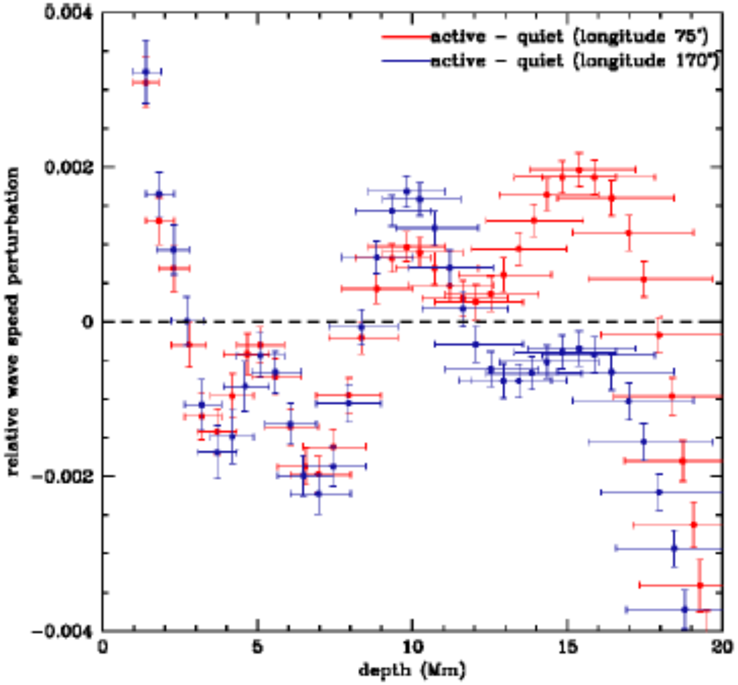

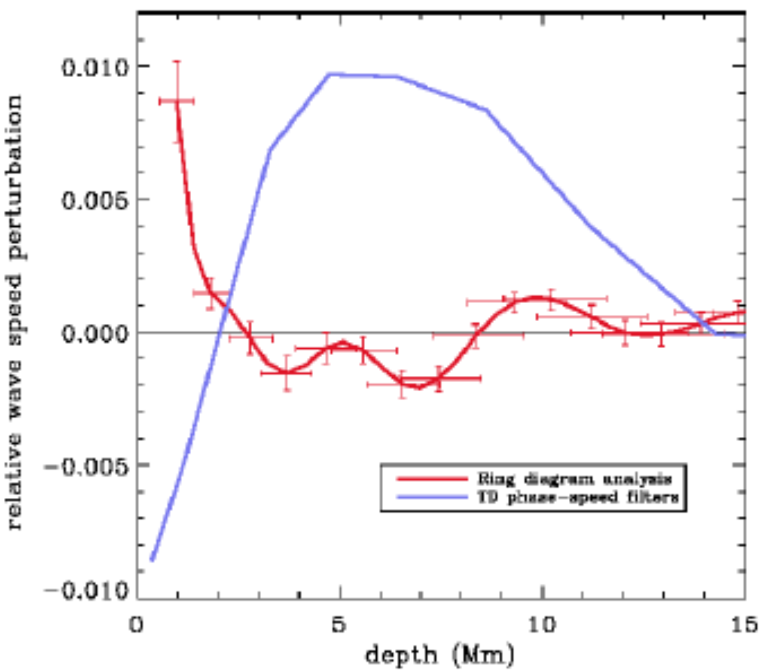

Clearly, they do not match.

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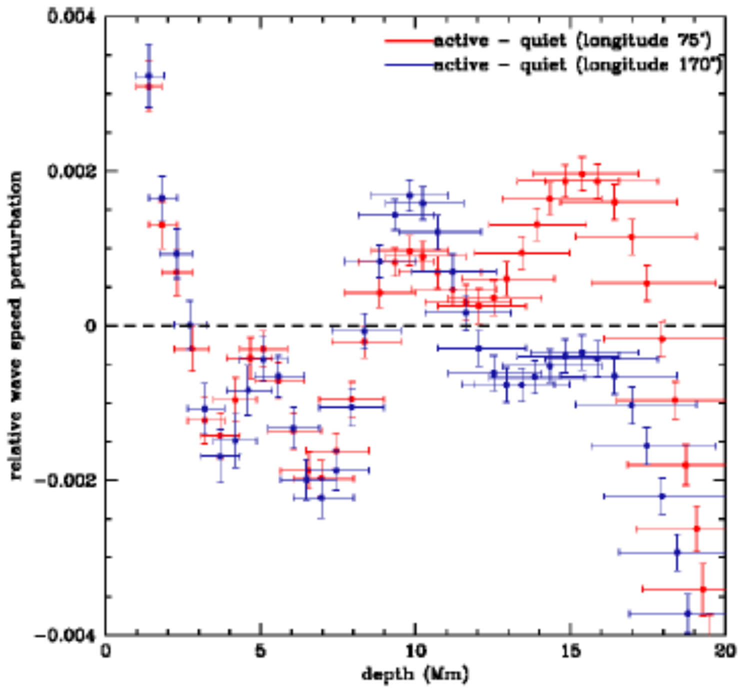
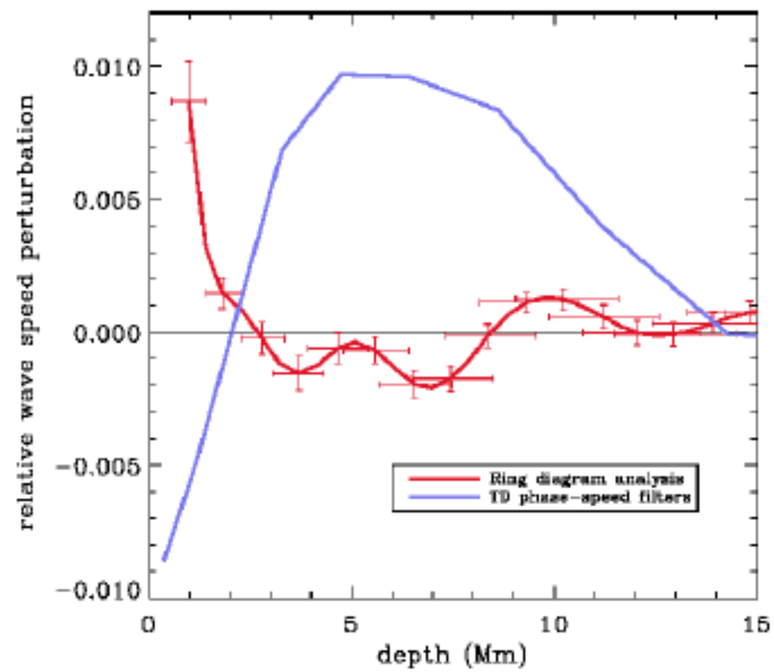


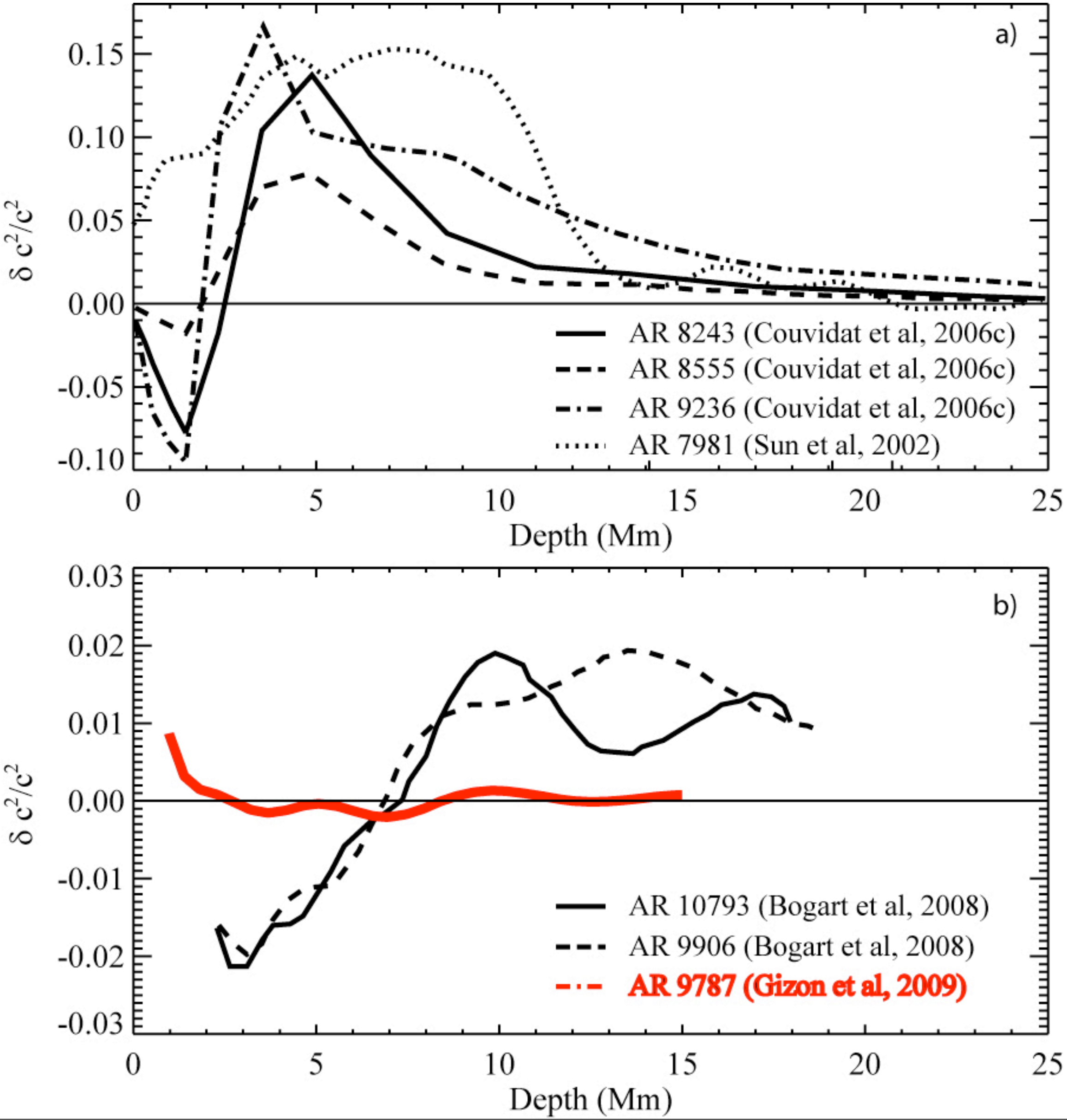


Clearly, they do not match.

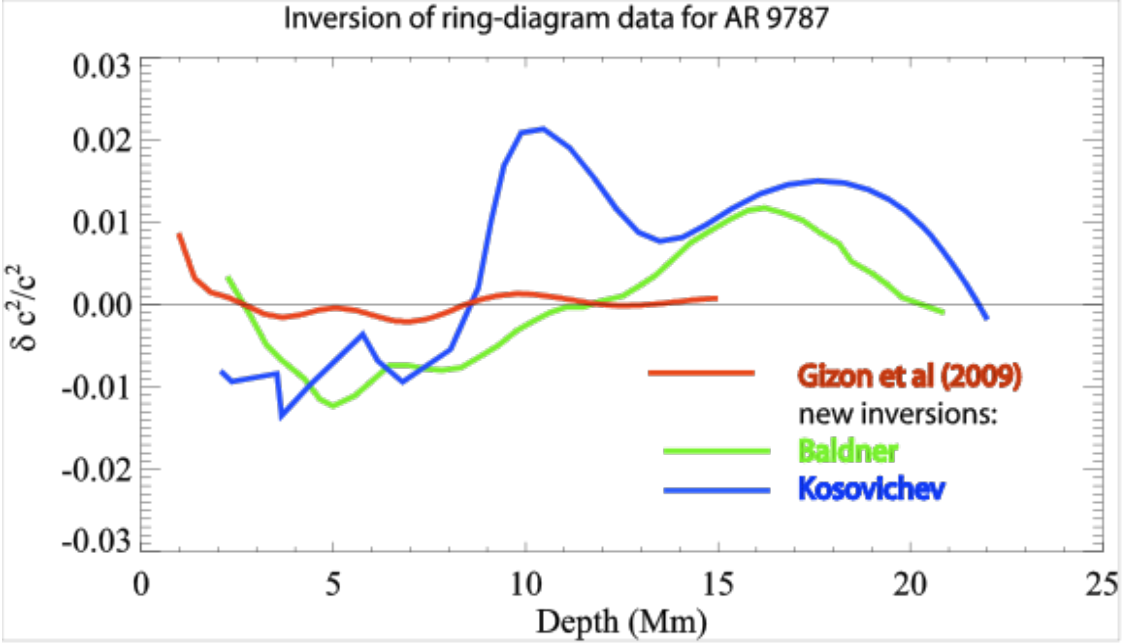
We also note that both inversions suppose that first-order perturbation theory is valid to describe the effect of sunspots on waves. Unlike the flow perturbation, however, the perturbations in pressure and density introduced by the sunspot are not small with respect to the quiet-Sun background. Thus the concept of linear inversions is not necessarily correct for sunspots and regions of strong magnetic field.

Sound-speed perturbations for several AR (top: time-distance and acoustic imaging; bottom: ring diagram results)

Comparison of time-distance and acoustic imaging inversions with ring-diagram results for various active regions shows qualitatively similar two-layer structures except the ring result for AR 9787 (Gizon et al 2009), which is also quite different from the time-distance inversion in this paper.



New ring-diagram inversions for AR9787 (Baldner and Kosovichev)



The new ring-diagram inversions for AR 9787 by Baldner (green) and Kosovichev (blue) showed significantly stronger perturbation in the deep interior than the results published by Gizon et al (red).

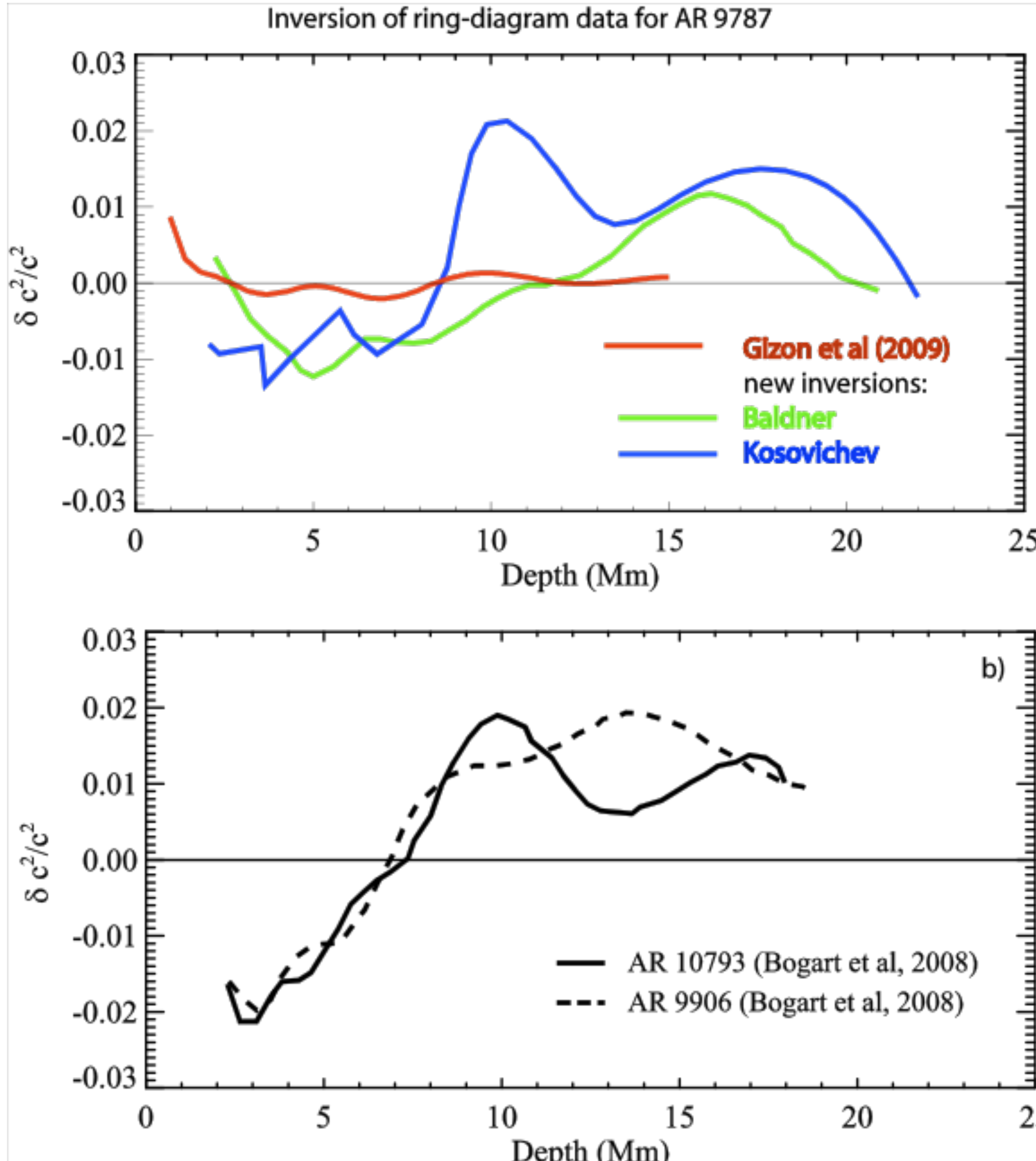
The new inversions were done independently using different codes and different choice of the secondary variables (density in Kosovichev's inversion and gamma in Baldner's inversion). The differences in the new inversion results are not yet understood, but they are more in line with the previous inversion results.

Comparison of the ring-diagram inversion for AR 9787 with the previous results for AR 9906 and 10793.

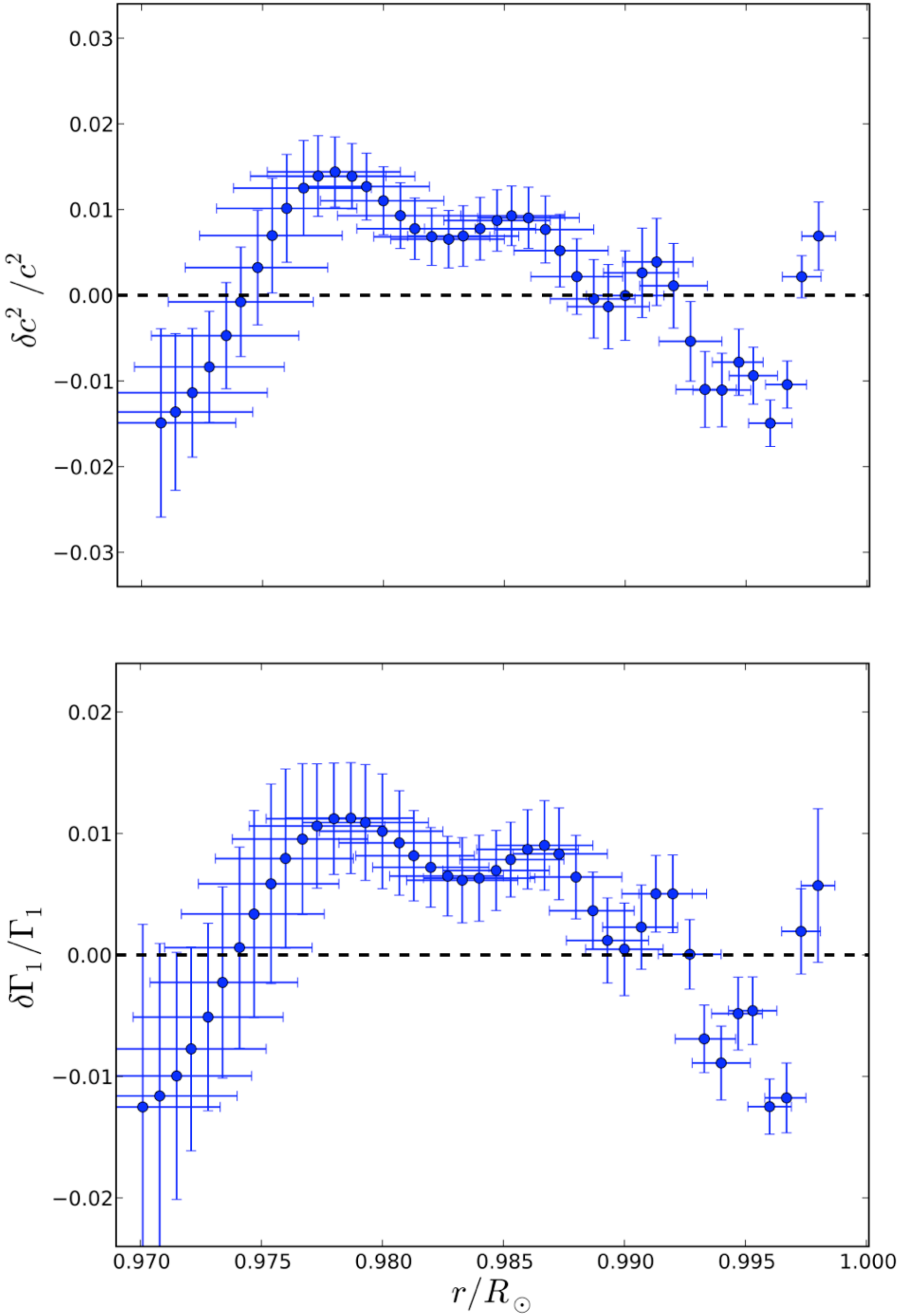
The inversions of Baldner and Kosovichev show weaker negative sound-speed perturbations than two other active regions studied by Bogart et al (2008).

This may be related to the unusually strong plage around the sunspot in AR 9787.

The plage probably make a significant contribution to the frequency shifts.

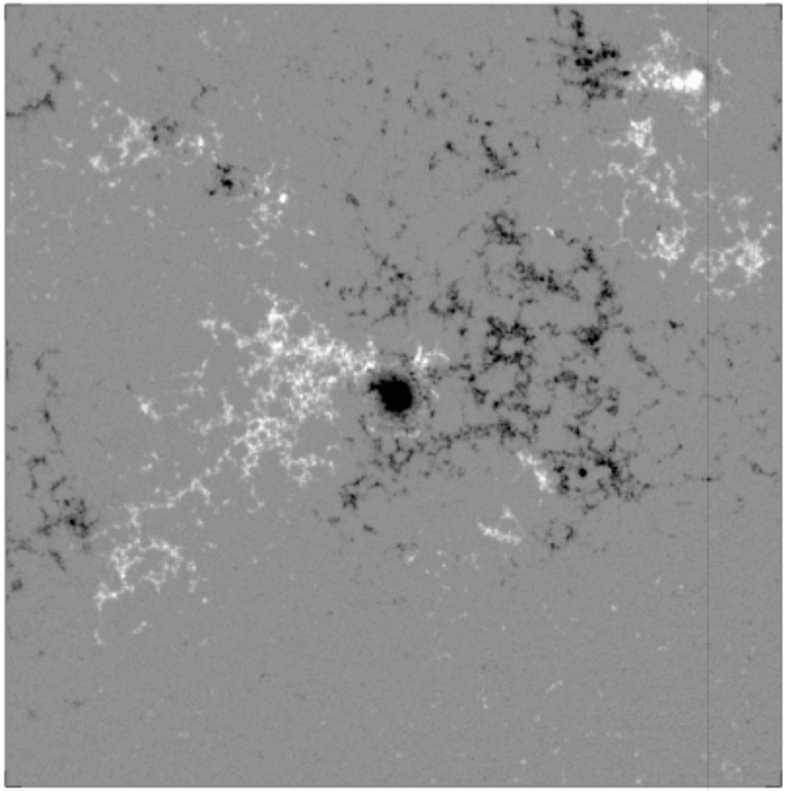


New ring-diagram inversions for AR 11072 from HMI data (Baldner *et al.*)

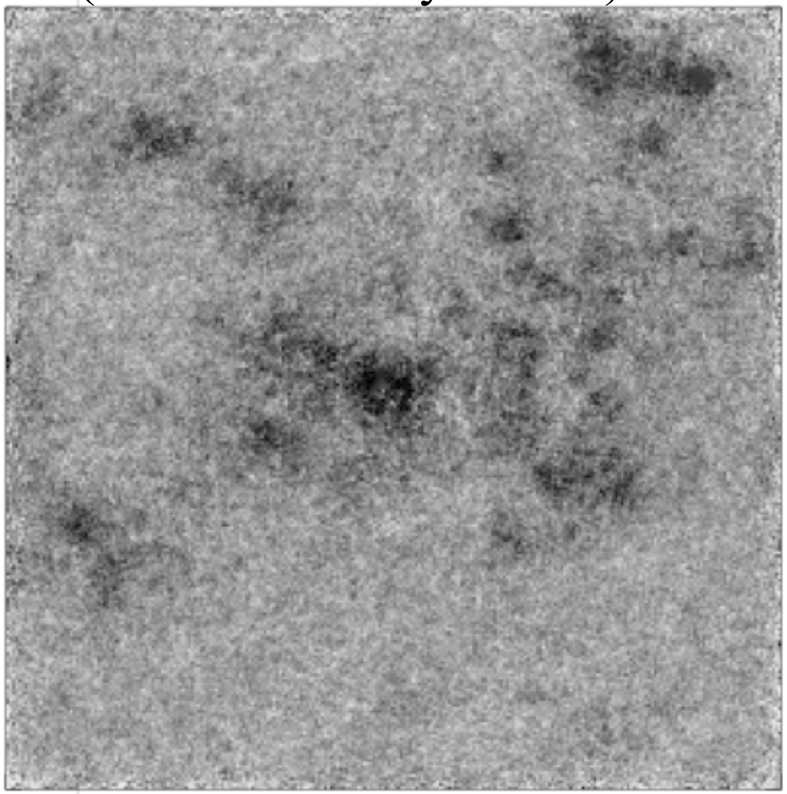


MDI magnetogram and travel-time map of AR9787

MDI magnetogram of AR 9787

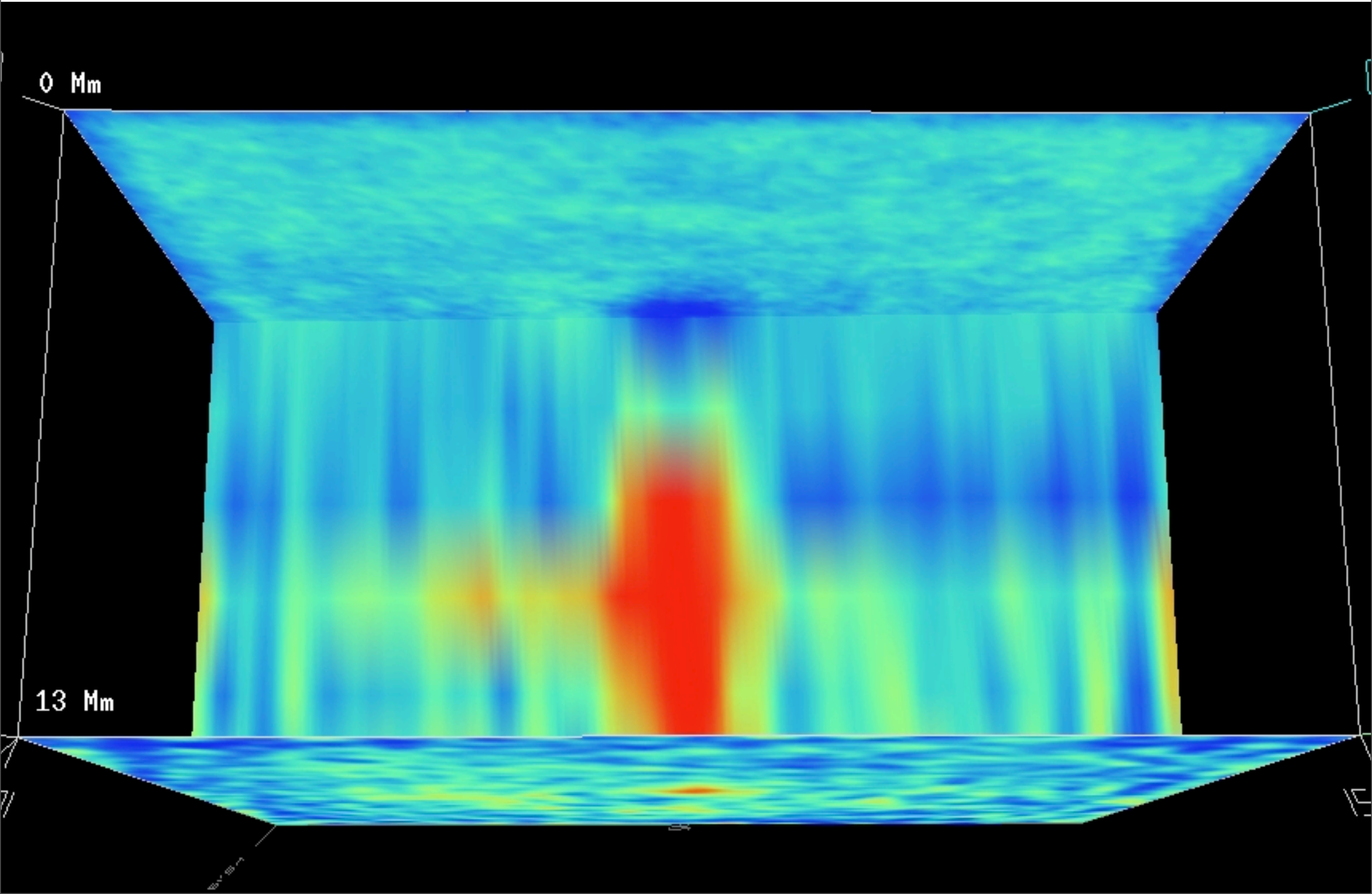


Travel-time map of AR 9787 (measurement by Duvall)



In AR 9787 the sunspot is surrounded by a large plage, which caused unusually strong perturbations of travel times. The plage probably contributed to the frequency shifts in the ring-diagram analysis, but it is unresolved. This causes difficulties in the comparison between the time-distance and ring-diagram inversions.

Sound-speed perturbation in AR 9787 obtained from MDI data using the HMI time-distance helioseismology pipeline



Conclusions

- We have made a new ring-diagram and time-distance helioseismology analyses of the subsurface sound-speed structure in AR 9787 and found that the inversion results are in a qualitative agreement with the previous results for other active regions.
- However, our results do not confirm the result published by Gizon et al (2009) that the sound-speed perturbation is very shallow and positive.
- The local helioseismology measurements show that it is likely that the sunspots and active regions have a significant positive perturbation of the sound-speed at the depth, 10-20 Mm (rings), 5-20 Mm (time-distance) and a negative perturbation in the shallow layer.
- The time-distance measurements show significant variations of the travel times in a large plage area outside the sunspot, comparable with the travel-time anomalies of the sunspot. Thus, it is difficult to make a quantitative comparison of the ring-diagram and time-distance results in this case. The frequency shifts measured by the ring technique are probably weighted with acoustic power, which is suppressed in sunspots and enhanced in plages.

Local Helioseismology Comparison (LoHCo) Group

- http://gong.nso.edu/science/meetings/lohco/

- **Local Helioseismology Workshop**

  August 2-6, 2010, Stanford

http://sun.stanford.edu/LH_Workshop_2010/