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Ring-Like Structures in the Travel-Time maps of Sunspots

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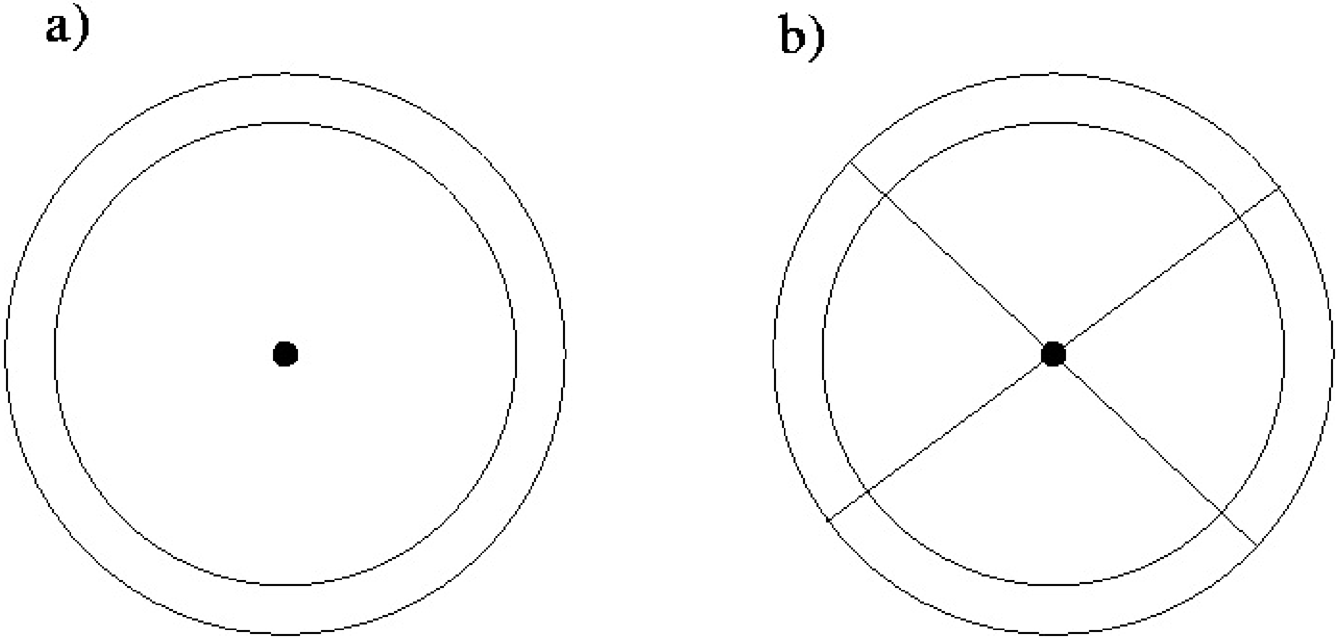
Time-Distance Helioseismology

- Phase-speed filtering of the Doppler velocity datacube (Duvall et al. 1997)
- Computing the point-to-point cross-covariances between source ($\mathbf{r}_1$) and receiver ($\mathbf{r}_2$)
- Different averaging schemes depending on the physical effect we are interested in [sound speed c(z), flow velocity $\mathbf{v}(\mathbf{r},z)$]



a) center-to-annulus averaging
b) east-west and north-south quadrant averaging

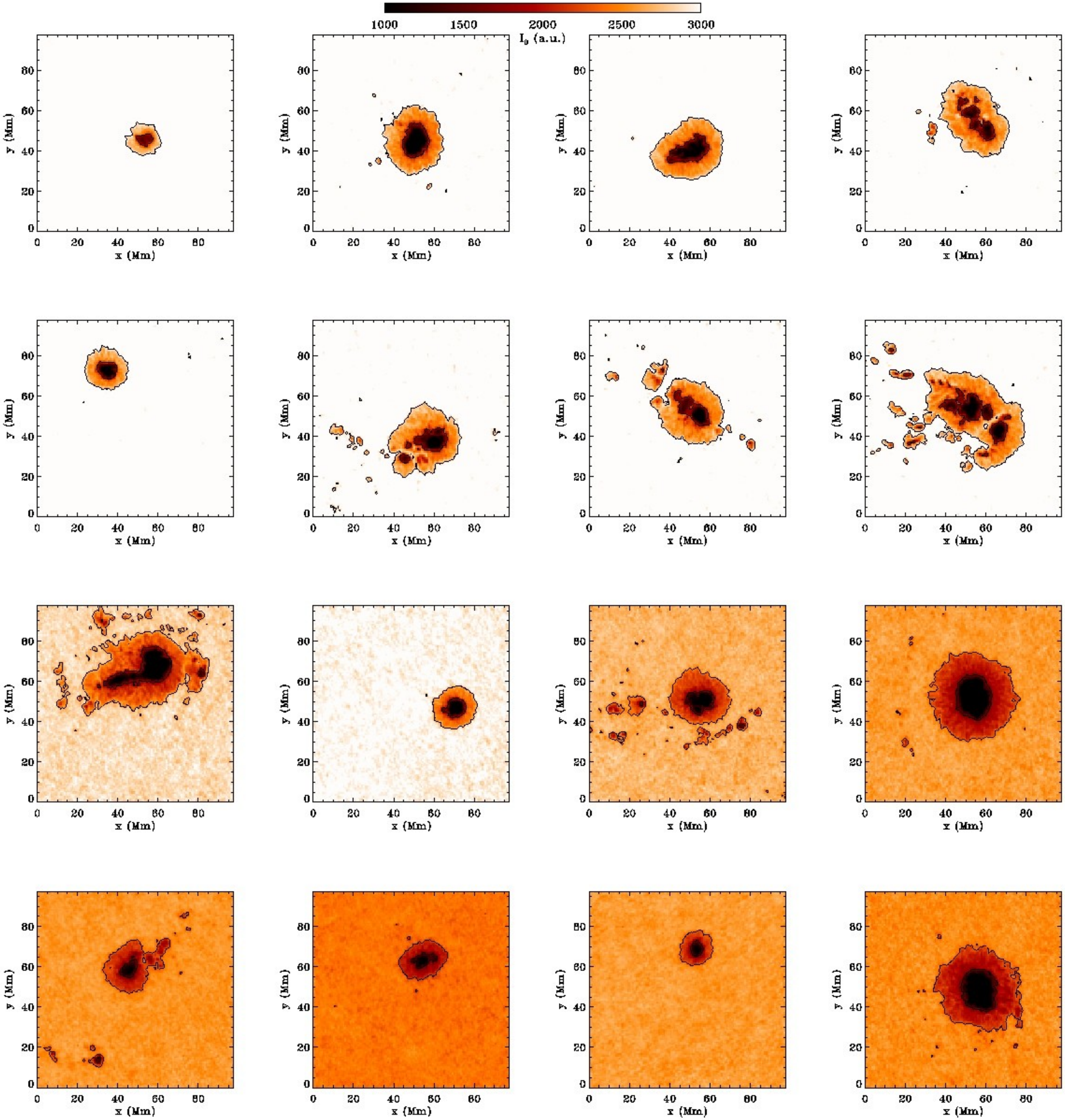
- Ingoing and outgoing travel time are fitted by Gabor wavelet (Kosovichev & Duvall 1997)

Inversion Algorithm

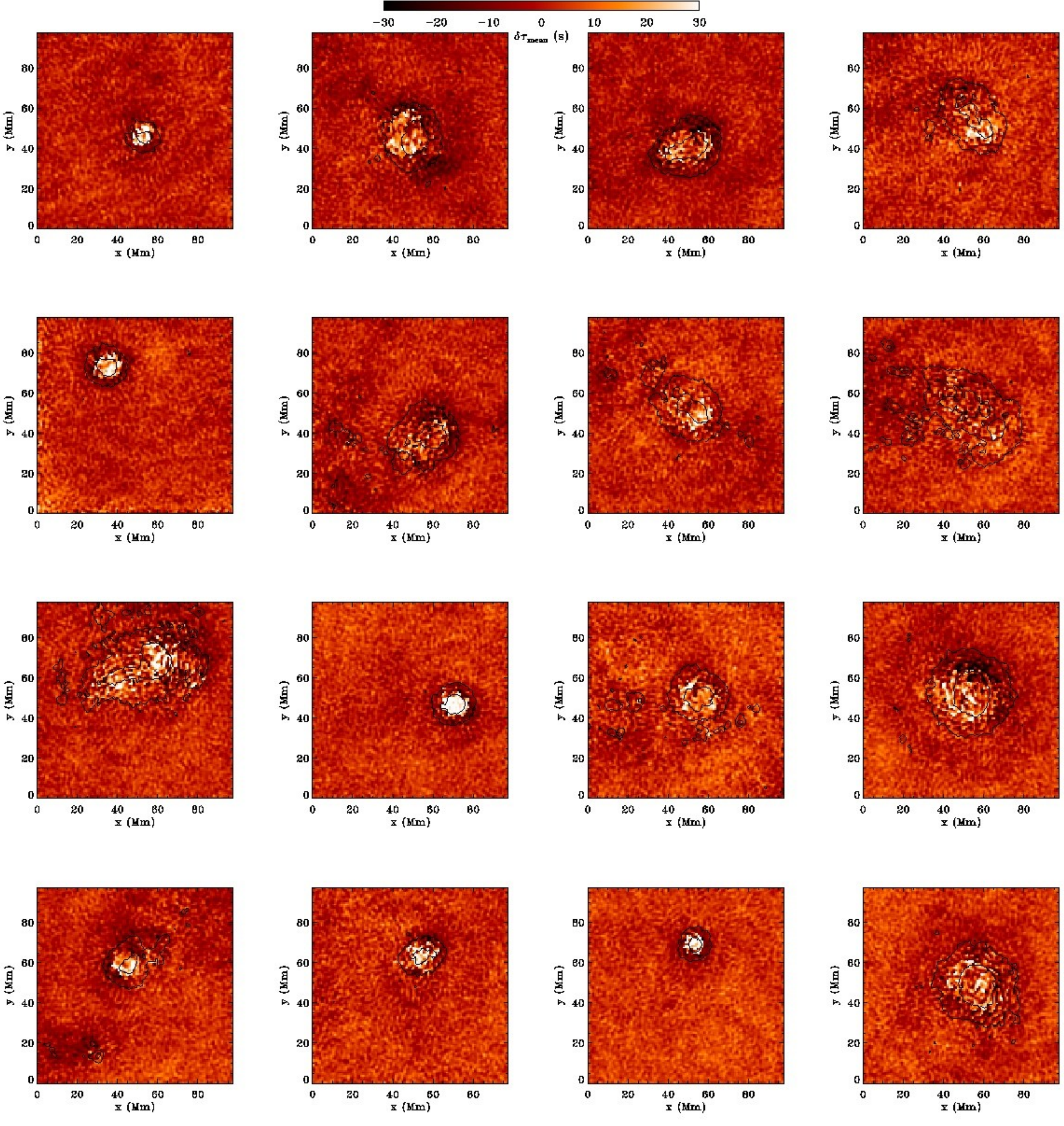
- We invert integral relations relating: i) mean travel-time perturbations to sound-speed perturbations ii) difference travel-time perturbations to flow velocities
- Based on MCD (Jensen, Jacobsen, & Christensen-Dalsgaard 1998)
- modified to include (Couvidat et al. 2005):
  - horizontal regularization
  - cross-covariance matrix of the noise on the travel-time maps (based on noise model by Gizon & Birch 2004)
- Uses 3 kinds of kernels:
  - Ray-approximation kernels (e.g. Giles 1999; Kosovichev, Duvall, & Scherrer 2000)
  - Fresnel-zone/Rytov-approximation kernels (Jensen & Pijpers 2003)
  - Born-approximation kernels (Birch, Kosovichev, & Duvall 2004)

Dataset

- Produced datacubes for 16 sunspots (between 1997 and 2006), with MDI Hi-Res data
- Datacubes: 256 x 256 x 512 nodes, dx=dy=0.826 Mm, dt=1 min
- Compute the mean and difference travel-time maps for these sunspots for 11 distances source-receiver
- Inverted the travel times using Born approximation kernels (provided by A. C. Birch), and modified MCD algorithm

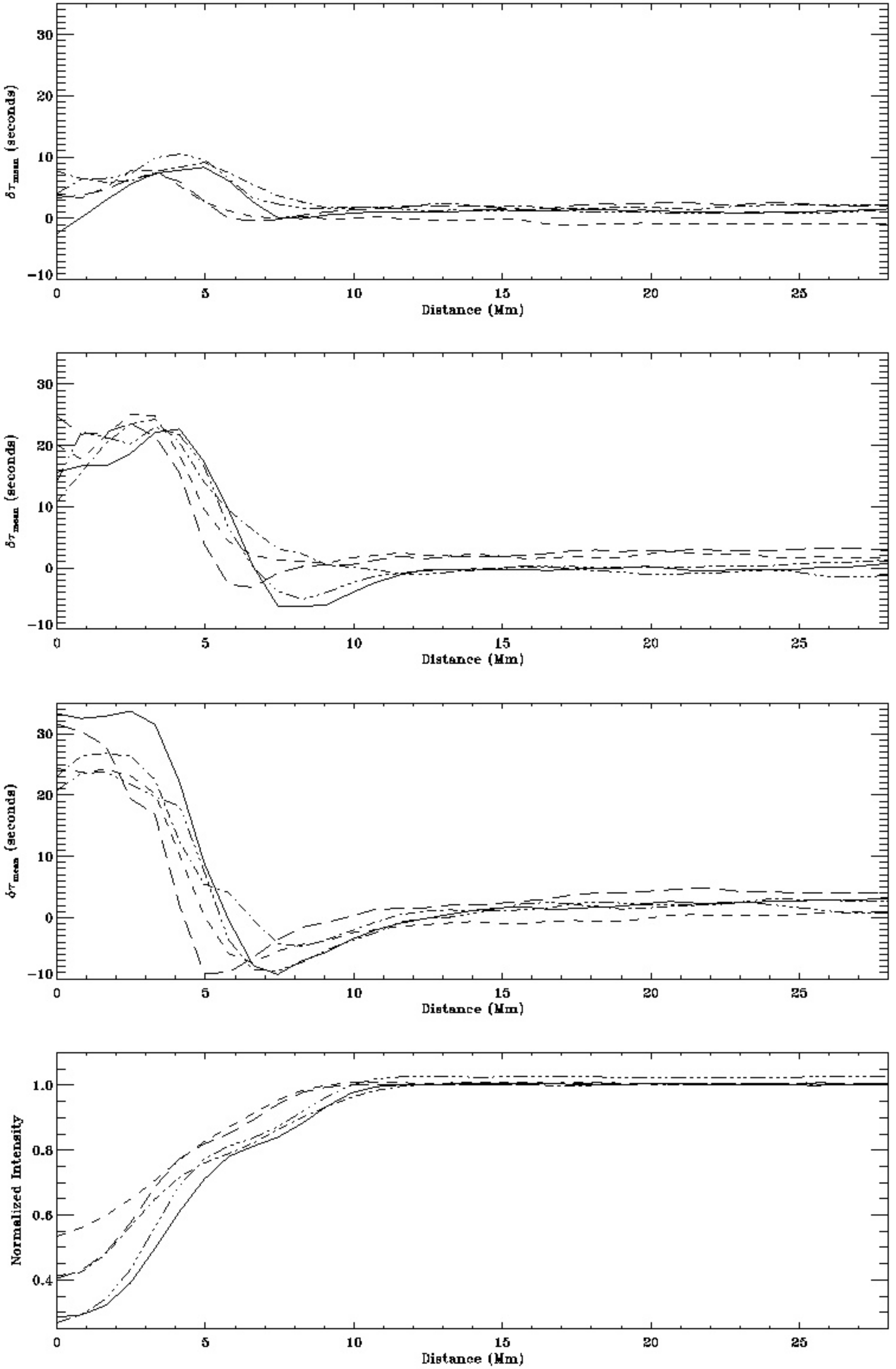


Continuum intensity maps of 16 solar active regions (From Couvidat & Rajaguru 2007)



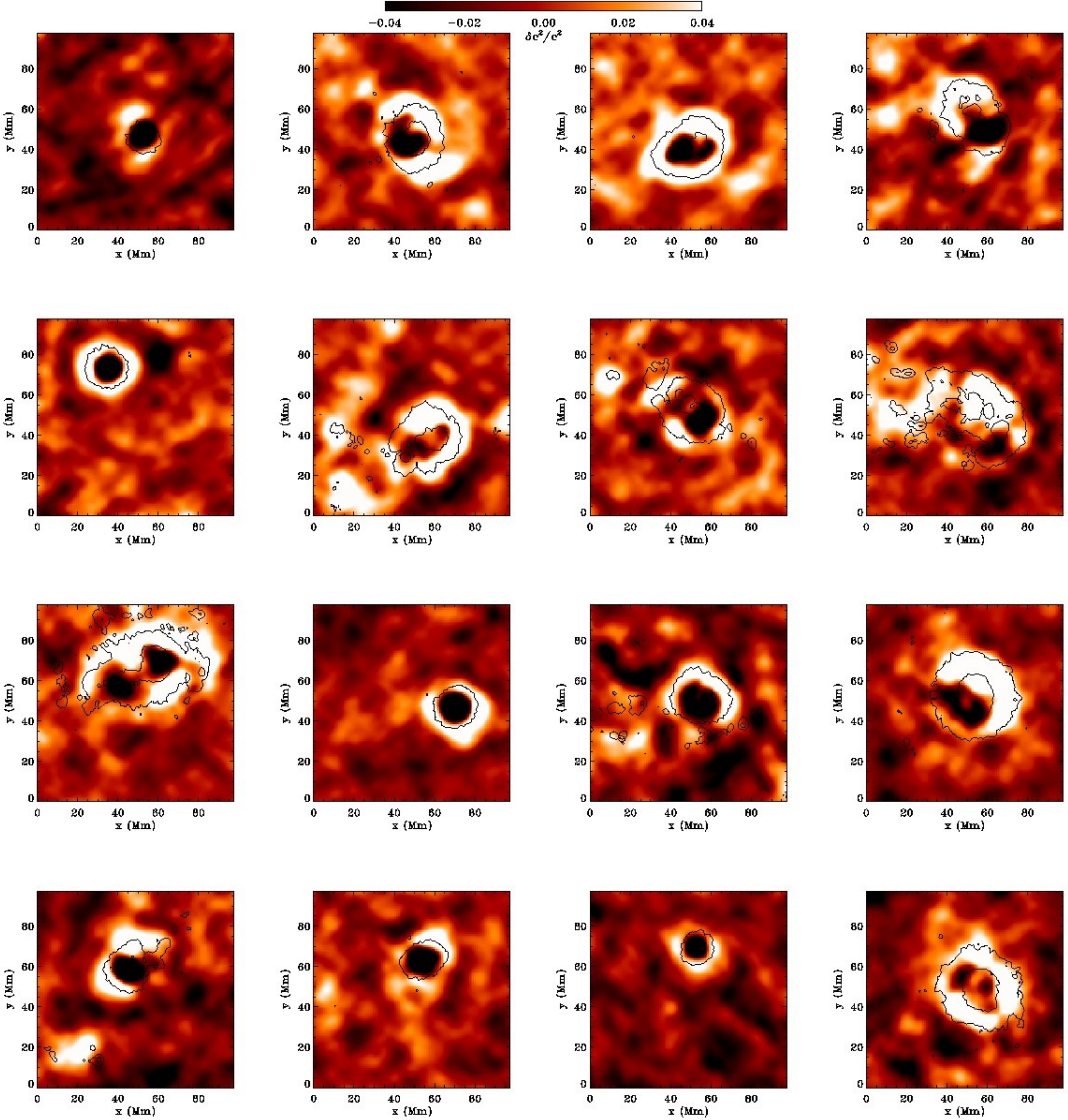
Mean travel-time perturbation maps at 11.6 Mm

(From Couvidat & Rajaguru 2007)



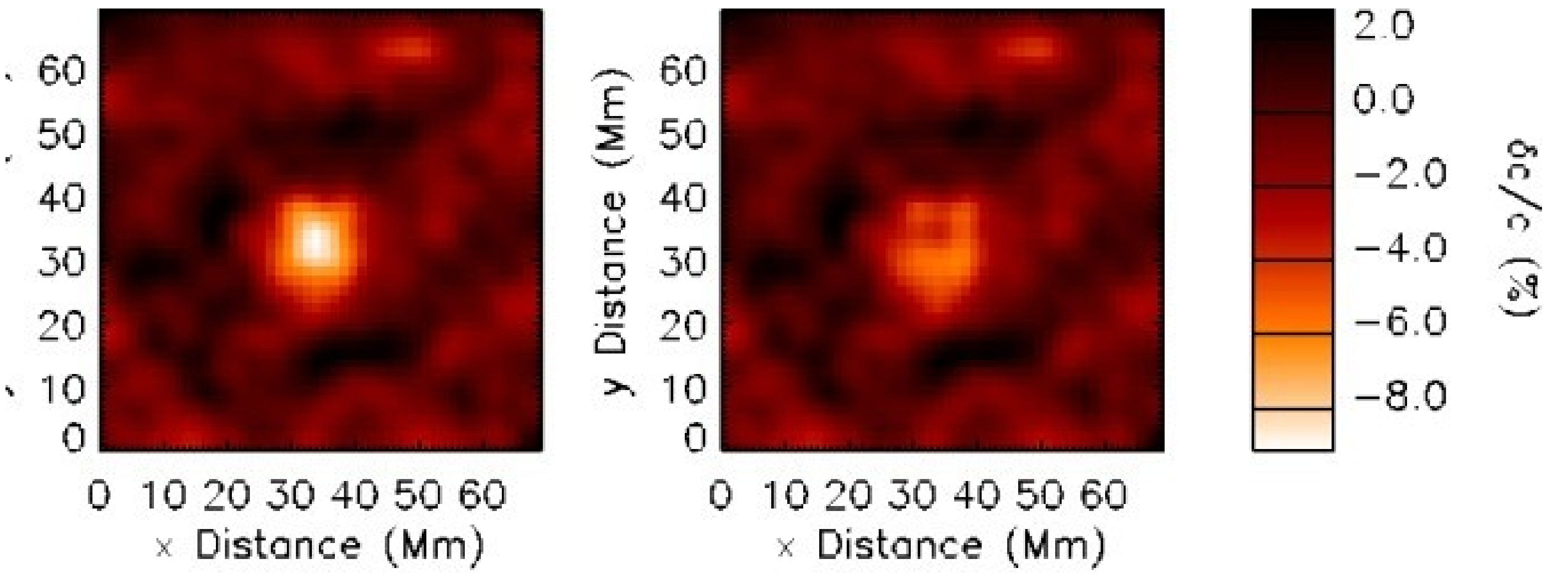
Azimuthal average of the mean travel-time perturbation for 5 circular sunspots, around the spot center at 6.2 Mm (upper panel), 8.6 Mm (middle), and 11.6 Mm (lower)

(From Couvidat & Rajaguru 2007)



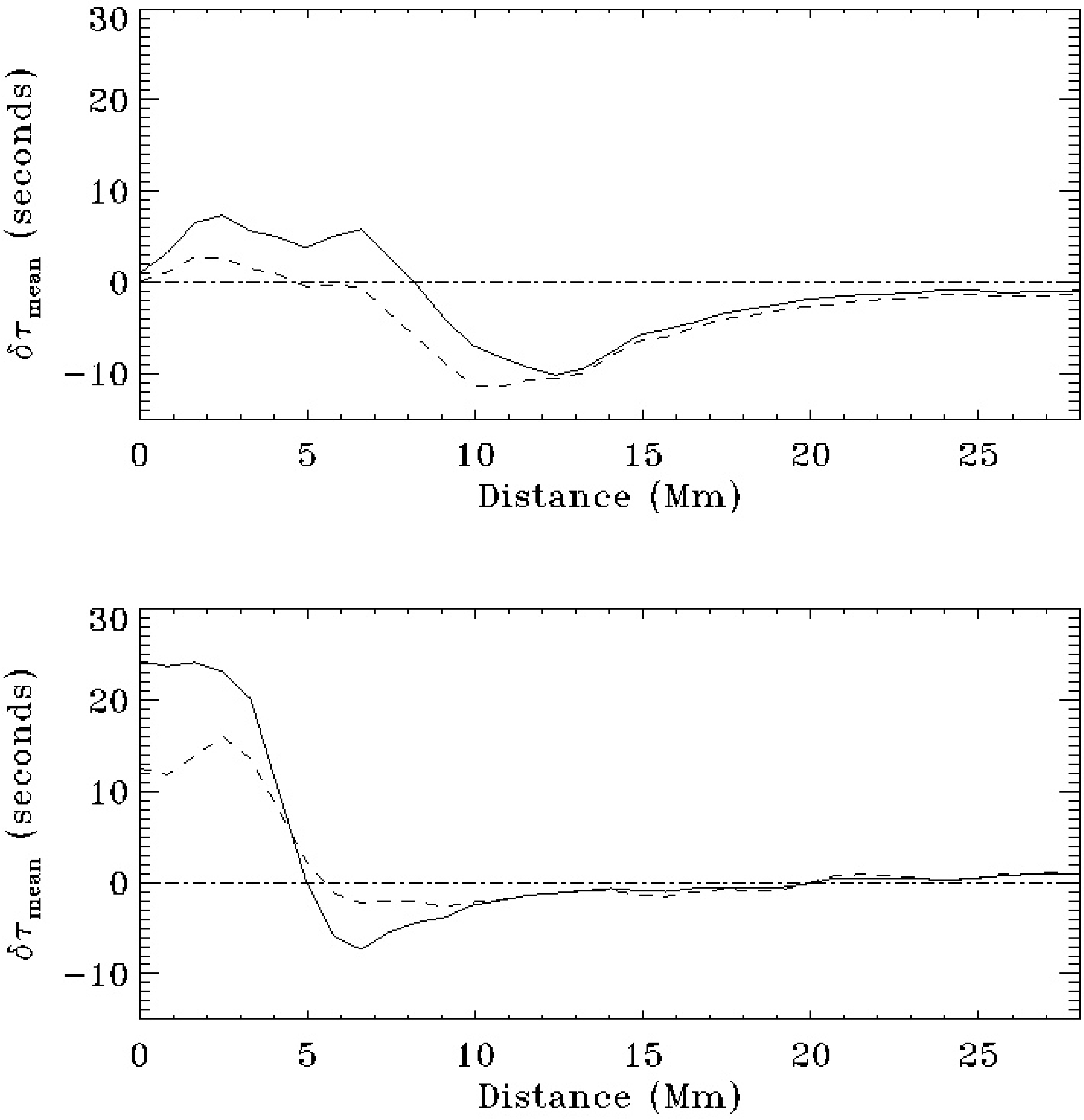
Relative sound-speed perturbation at a depth of z=-2.38 to z=-1.42 Mm

(From Couvidat & Rajaguru 2007)

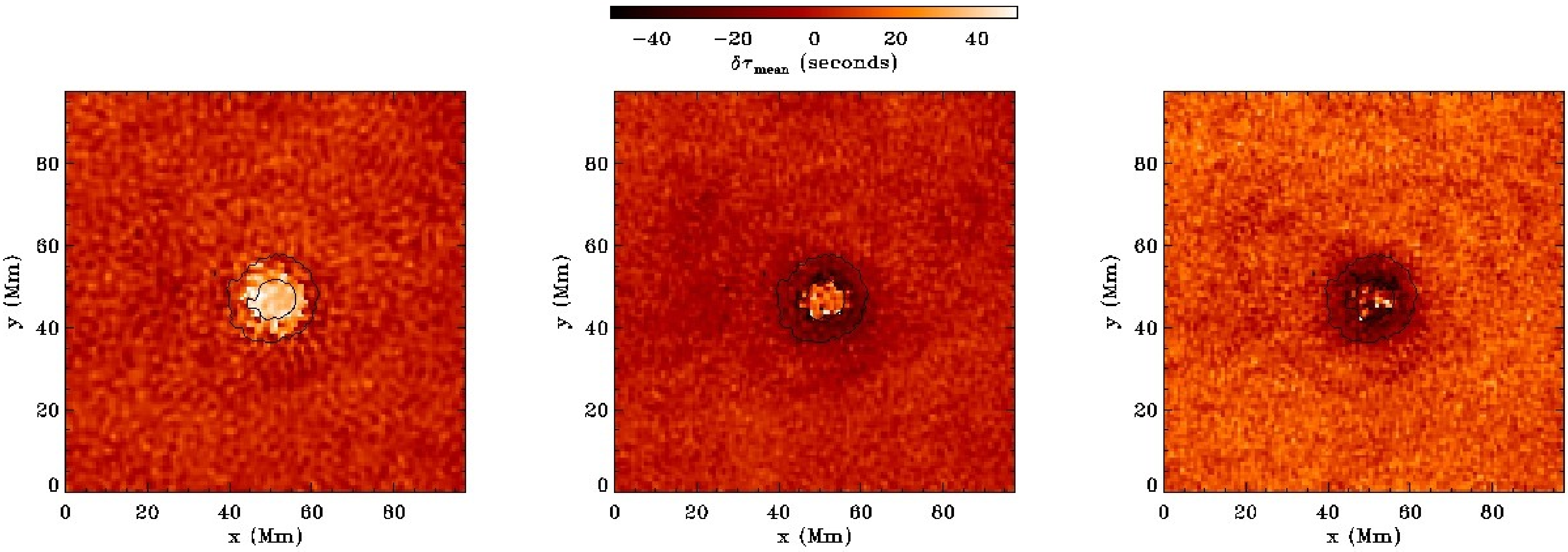


Relative sound-speed perturbation at a depth of z=-2.38 to z=-1.42 Mm with GONG data (left panel: all data, right panel: cropped data)

(From Hughes, Rajaguru, & Thompson 2005)

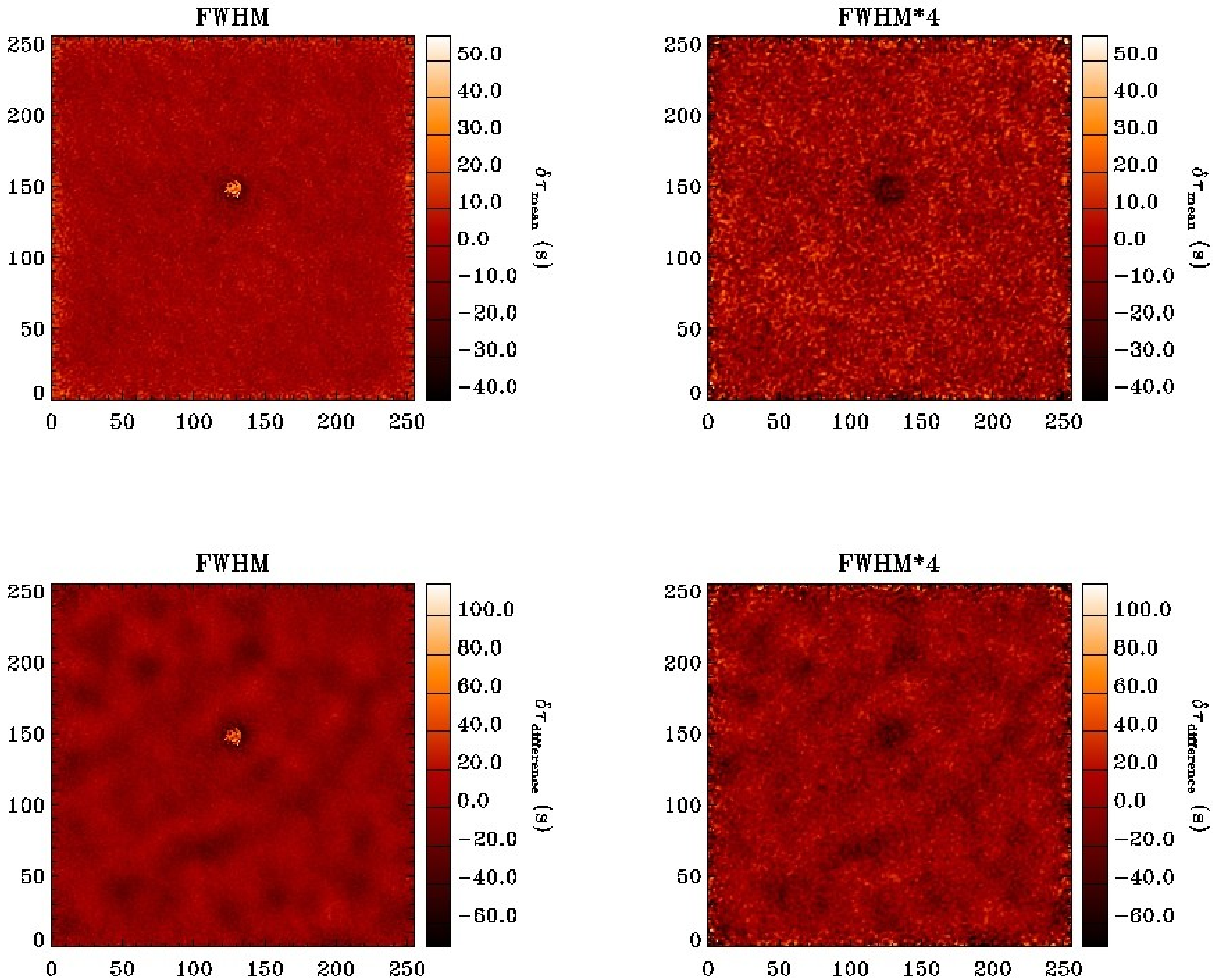


Upper panel: azimuthal average of the mean travel time for 11.6 Mm and NOAA 8397. Solid line: before power correction of Rajaguru et al. (2006); dashed line: after correction. Lower panel: same plot for NOAA 8073.

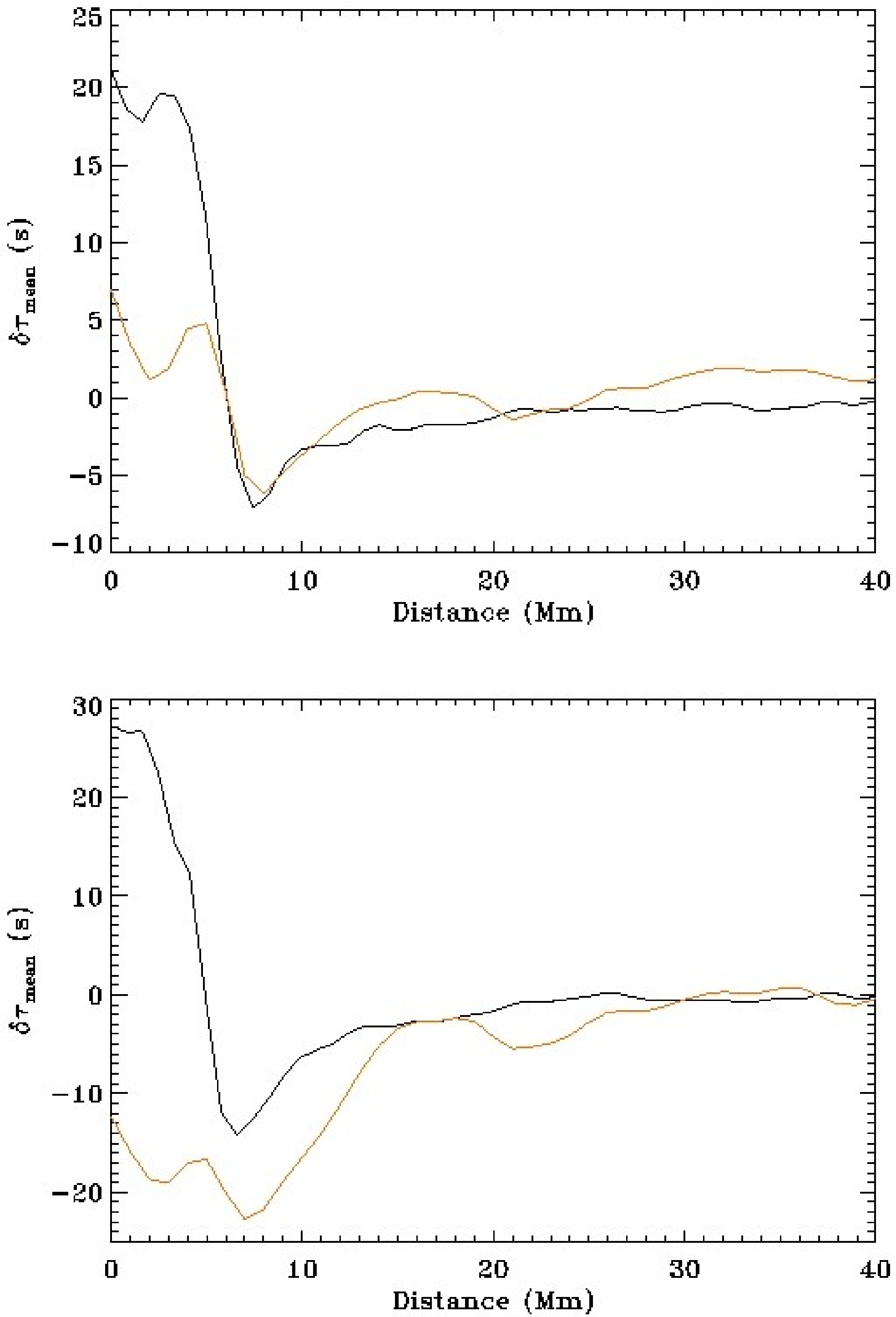


Mean travel-time perturbations in 3 different frequency bands: around 3 mHz (left panel), 4 mHz (central), and 4.5 mHz (right) for a distance of 11.6 Mm

(From Couvidat & Rajaguru 2007)



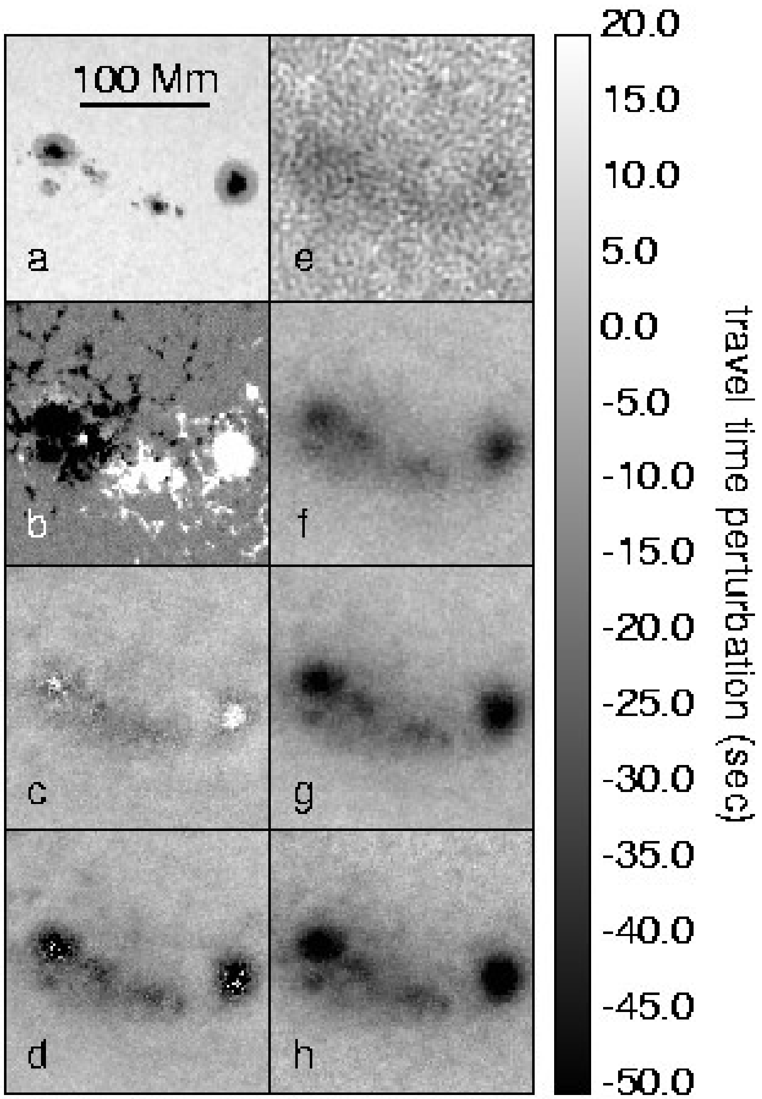
Mean (upper panels) and difference (lower panels) travel-time perturbations at 11.6 Mm for NOAA 0689 and for two widths of the phase-speed filters



Azimuthal average of the mean travel-time perturbations at 8.7 Mm (upper panel) and 11.6 Mm (lower panel) for NOAA 0689 and for two widths of the phase-speed filters (standard width in black, 4 times the standard width in red)

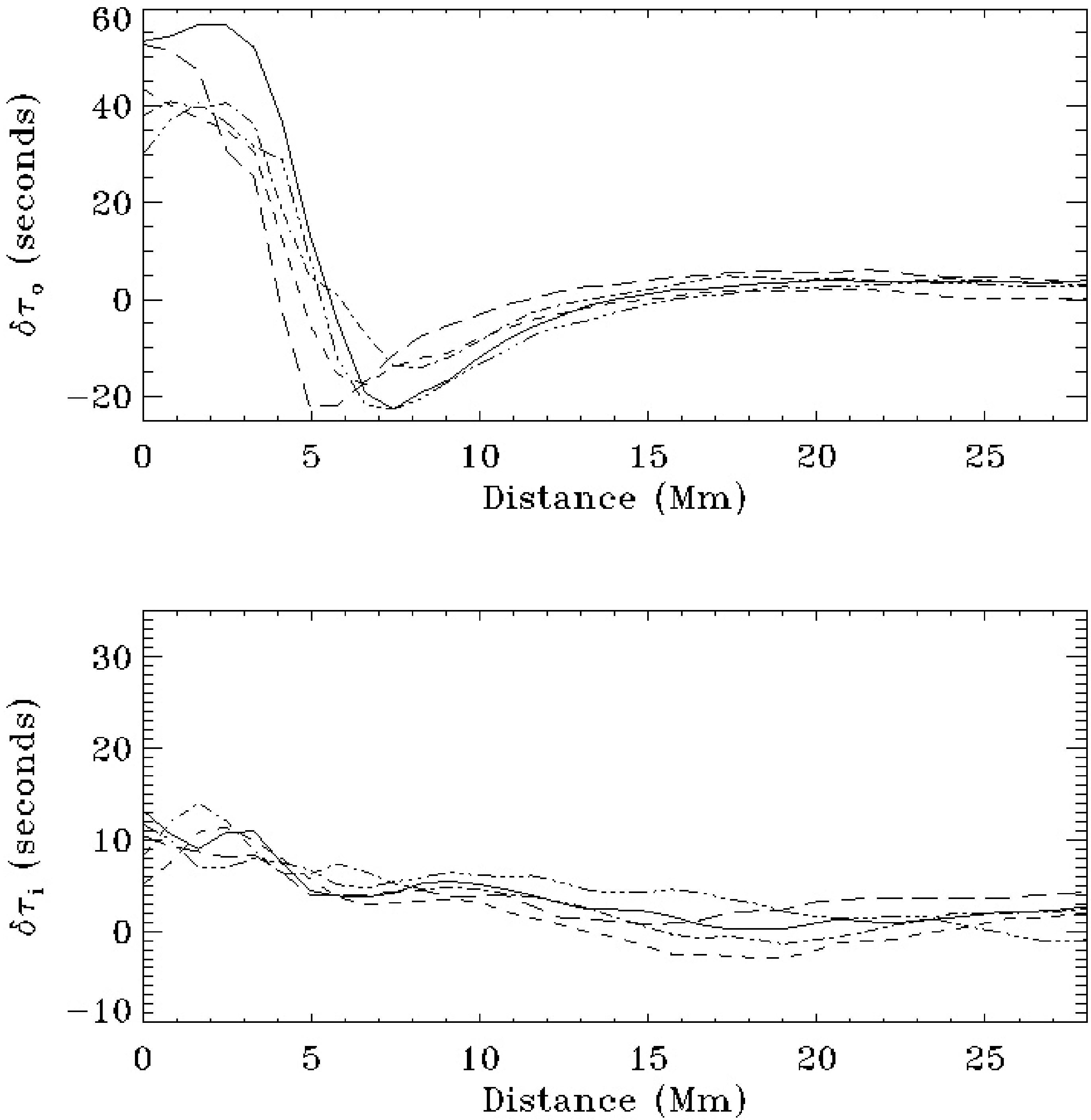
Frequency dependence of travel times

- Chou, Sun, & Chang (2000), Chou & Duvall (2000), Braun & Birch (2006) observe a frequency dependence of travel times in sunspots



Panels (a): SOI/MDI continuum intensity; (b): line-of-sight magnetogram, (c) to (h): sample maps of the mean travel-time perturbation covering a portion of the region studied and showing sunspot group AR 9885. Panels (c) and (d) show travel-time maps for a specific phase-speed filter and a frequency filter centered at 3 and 4 mHz respectively. Panels (e) to (h) show the travel-time maps for another phase-speed filter and the frequencies 2, 3, 4, and 5 mHz respectively.

From Braun & Birch (2006)



Azimuthal average of outgoing (upper panel) and ingoing (lower panel) travel time shifts for 5 sunspots and for the distance 11.6 Mm

(From Couvidat & Rajaguru 2007)

Origin of these ring-like structures ?

- ✓Rings are mainly below penumbrae in inversion results/ inside penumbrae on travel-time maps
- ✓Rings are only present on outgoing travel times
- ✓Rings are very sensitive to the filtering applied to datacubes (strong frequency dependence)
- ✓Frequency dependence similar to what Braun & Birch (2006) observed
- ✓Cally (2000), Crouch & Cally (2003), Schunker et al. (2005) emphasize the effects of an inclined magnetic field on the acoustic wavefield
- ✓Lindsey & Braun (2005) observe an anomaly in the seismic signature of sunspot penumbra (penumbral acoustic anomaly)

=> artifacts produced by interaction of surface magnetic field and acoustic waves ?