Subsurface Structures and Flows in Active Regions and Polar Areas Obtained from *Hinode*

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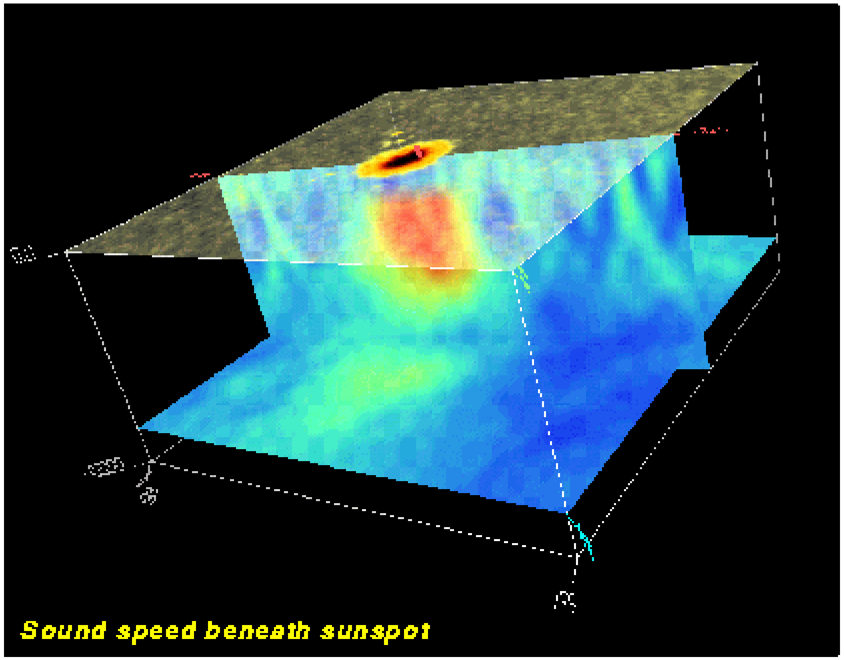
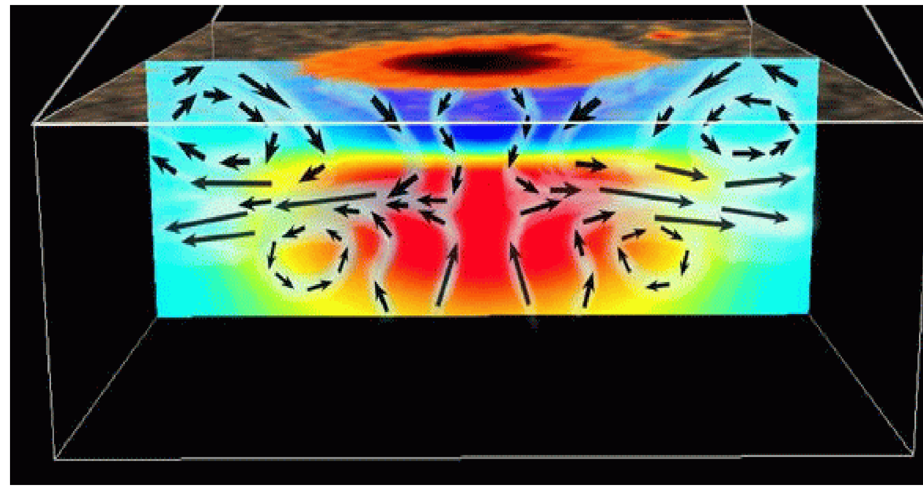
Subsurface Structure and Flow Fields from MDI Dopplergrams



Sunspot data from MDI High Resolution, 18 June 1998

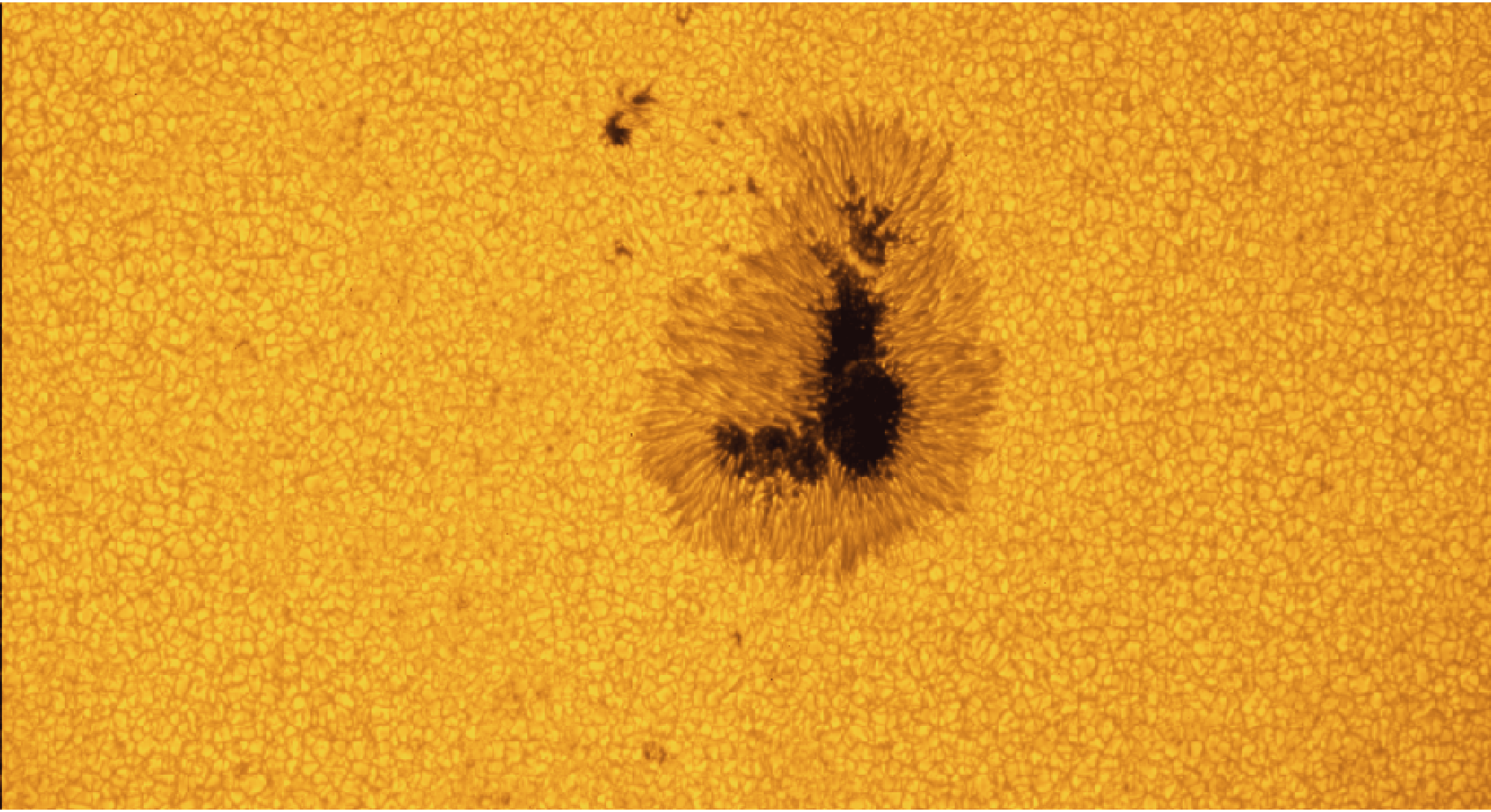


Red indicates faster sound speed, and blue indicates slower sound speed. Downward and inward flows are found immediately below the sunspot’s surface.

Basically, up to now, only SOHO/MDI observations are able to give a high-resolution picture of subsurface flow fields and structures. Does Hinode have such a capability to infer subsurface properties of active regions? And do they agree with MDI results?

There have been a lot of arguments in favor and against the MDI active region subsurface pictures. Here, I cannot address all of those arguments, but like to use Hinode observations to address some very important issues that cannot be done using MDI.

The Active Region We Study: Sunspot "Japan"



AR 10953 of May 2, 2007

Data Processing

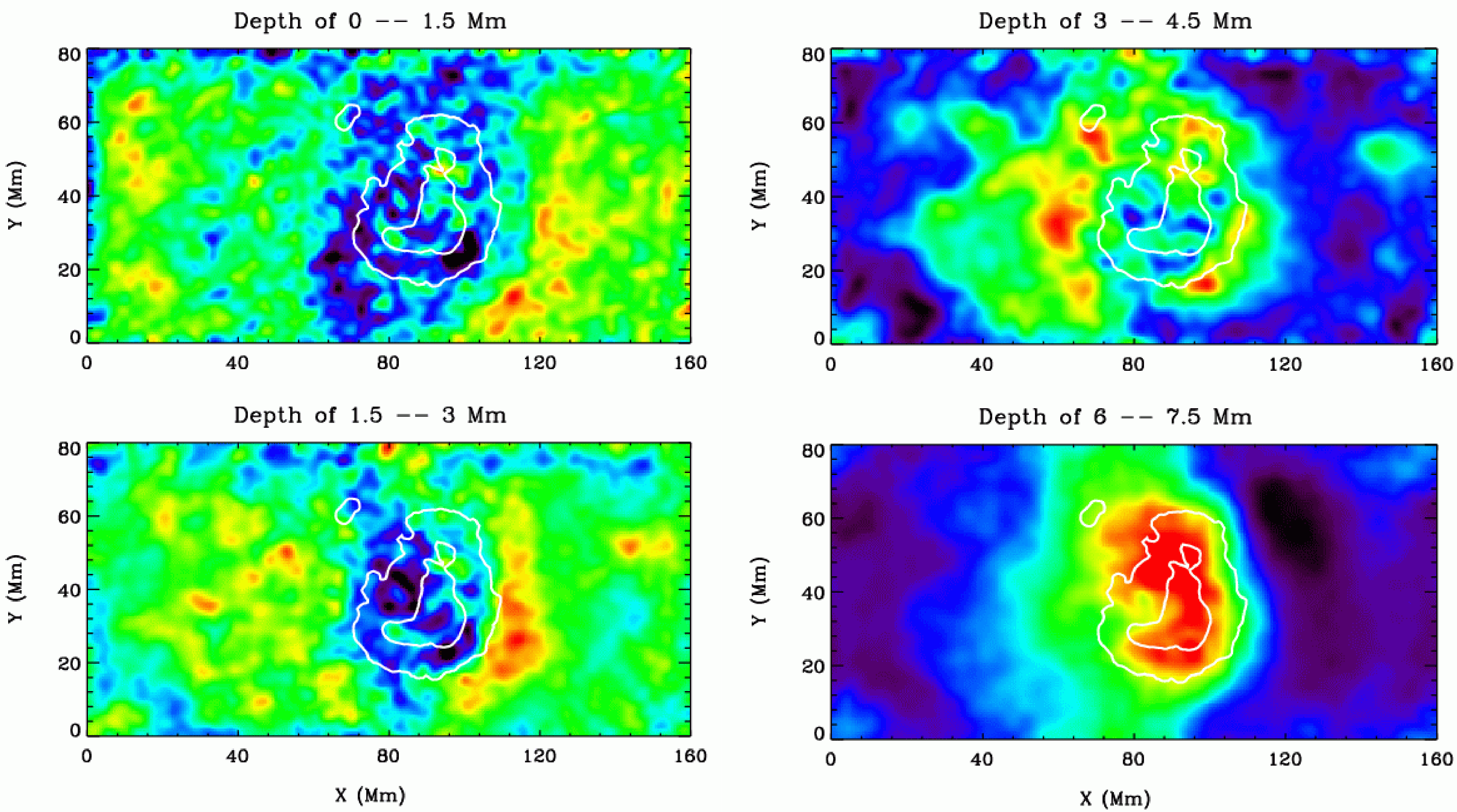
- The observation was from 17:00UT, May 2 to 05:58UT of May 3, 2007 with continuous coverage of one minute cadence. That is 738 minutes in total.

- CaH observation is used for time-distance helioseismology analysis. And, running differences of images are used to remove convections and other low frequency signals.

- To perform time-distance measurements, the following annulus radii are used: 4.0 – 6.6, 6.5 – 9.7, 9.2 – 12.5, 12.0 – 15.9, 15.1 – 18.9, 18.5 – 22.3, and 21.6 – 25.4Mm.

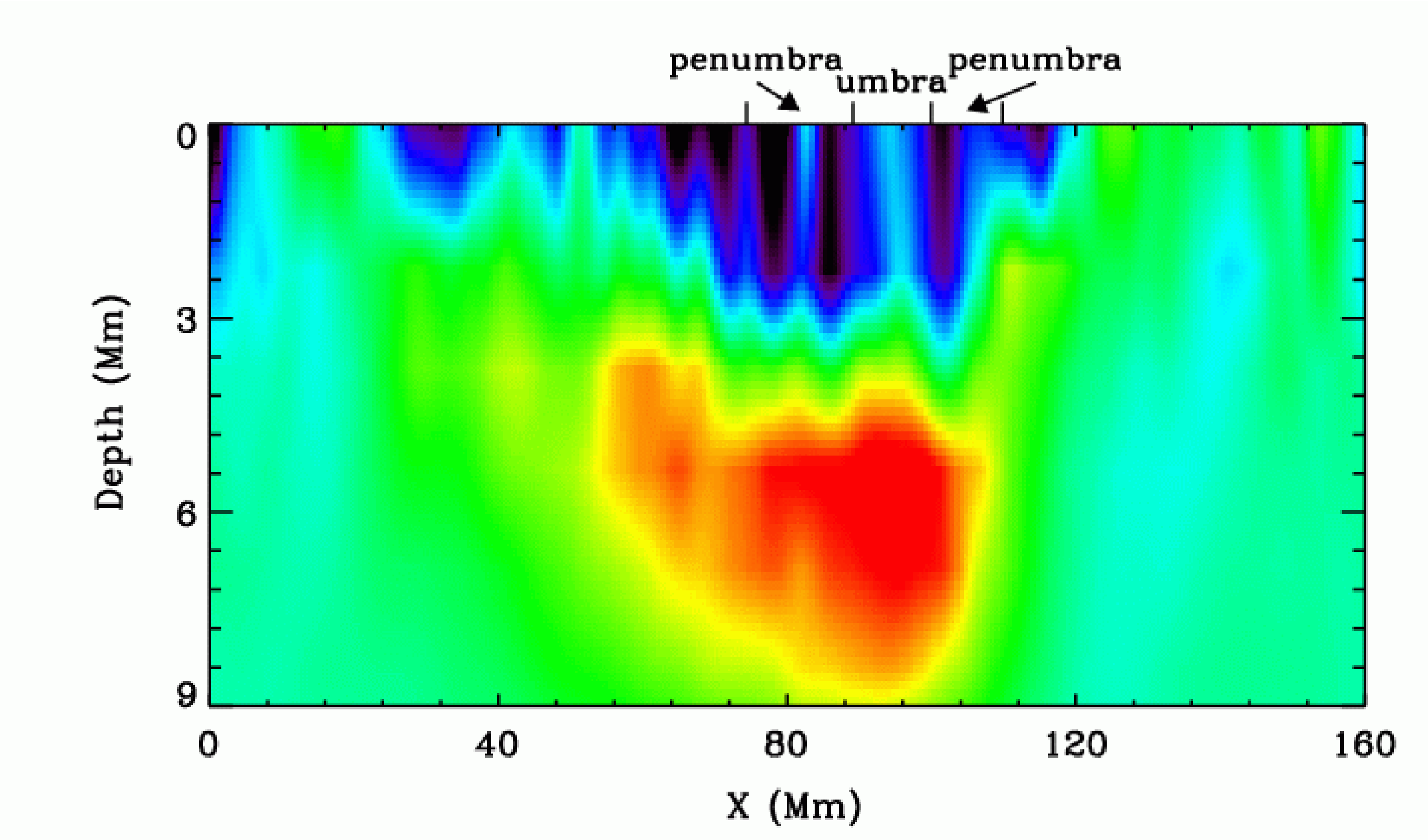
- After acoustic travel times are measured, inversions are performed using Multi-Channel Deconvolution technique, and ray-approximation sensitivity kernels.

Subsurface Structure of Sound Speed Perturbation



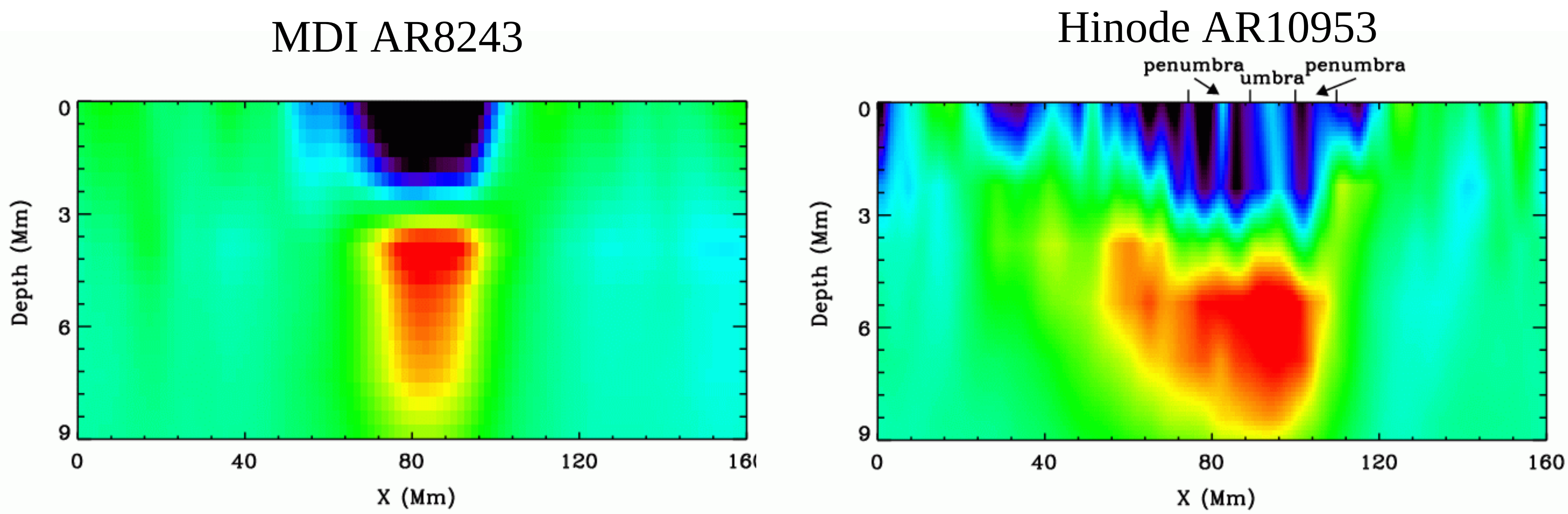
Blue indicates negative sound speed perturbation, and red indicates positive.

Vertical Subsurface Structure



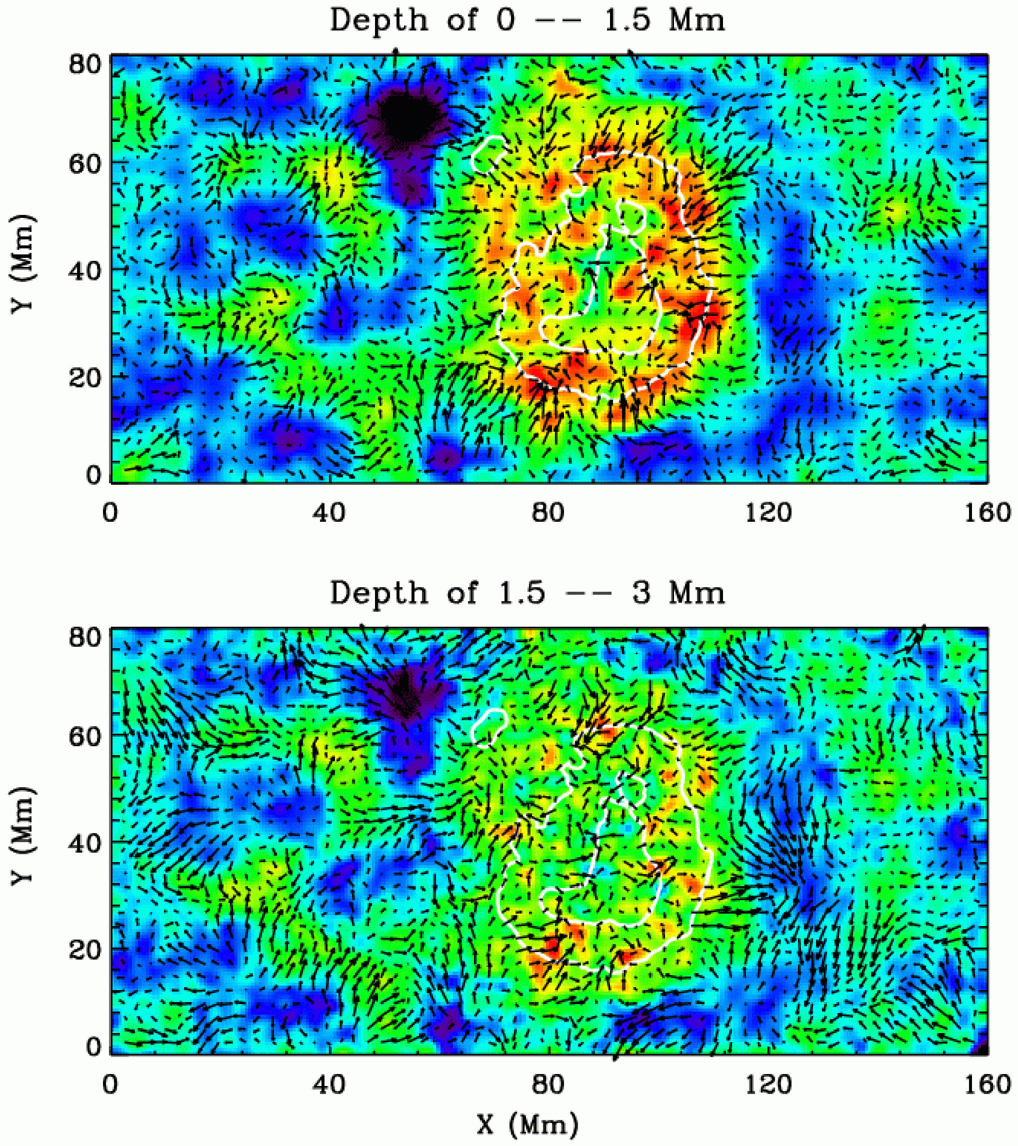
The sound speed perturbation extends far beyond the sunspot area. Due to the limit of the field of view of observation, the sound speed perturbation cannot be derived deeper than 9 Mm or so.

Comparing MDI and Hinode Sunspot Subsurface Structure



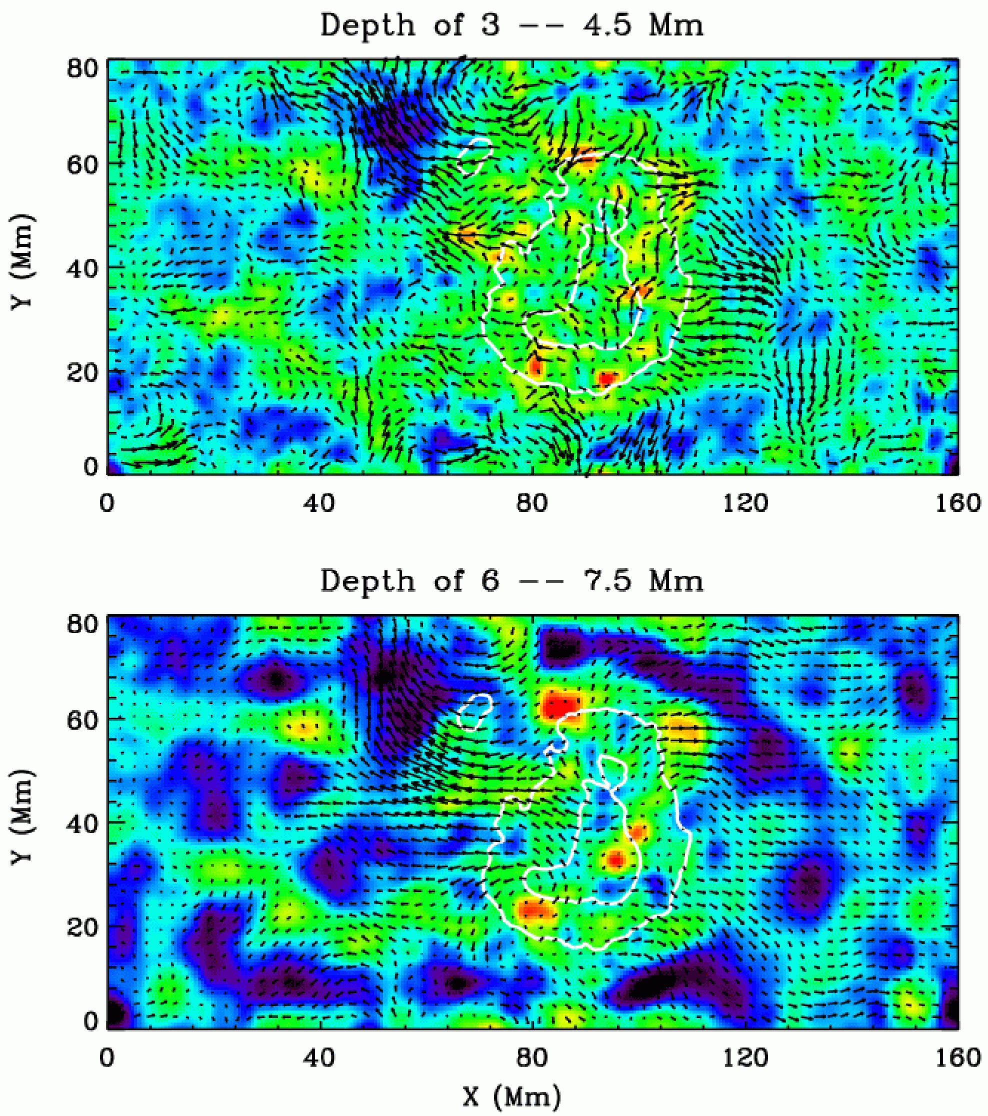
Note that the two studies are for two different active regions, and the sizes of sunspots are also different. However, the negative and positive sound speed perturbation structures look similar, and the conversion depth is similar.

Subsurface Flow Fields



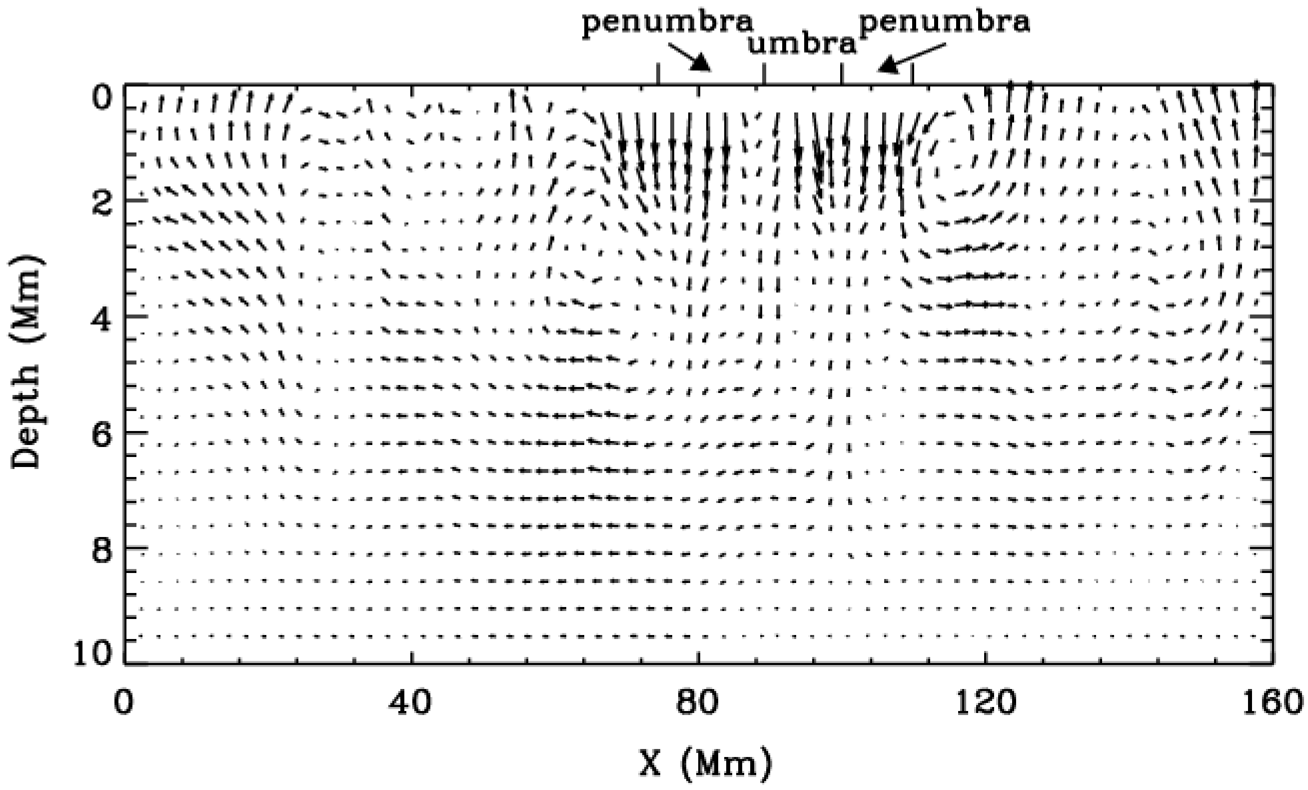
Background image shows vertical flow fields, with red as downward flows, and blue as upward flows. The order of magnitude of flows is 500 m/s.

Subsurface Flow Fields



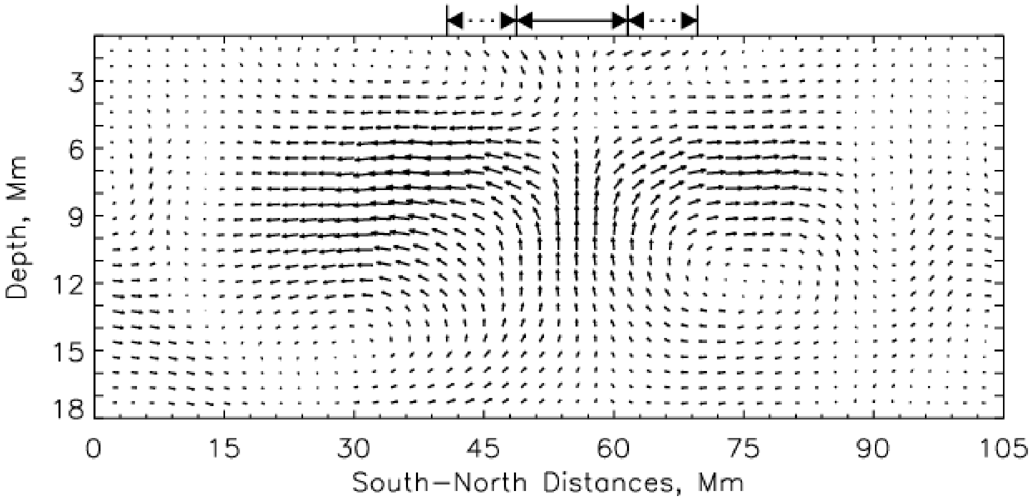
Up to 7Mm down below the surface, it seems that downward flows are still strong. This is different with MDI results.

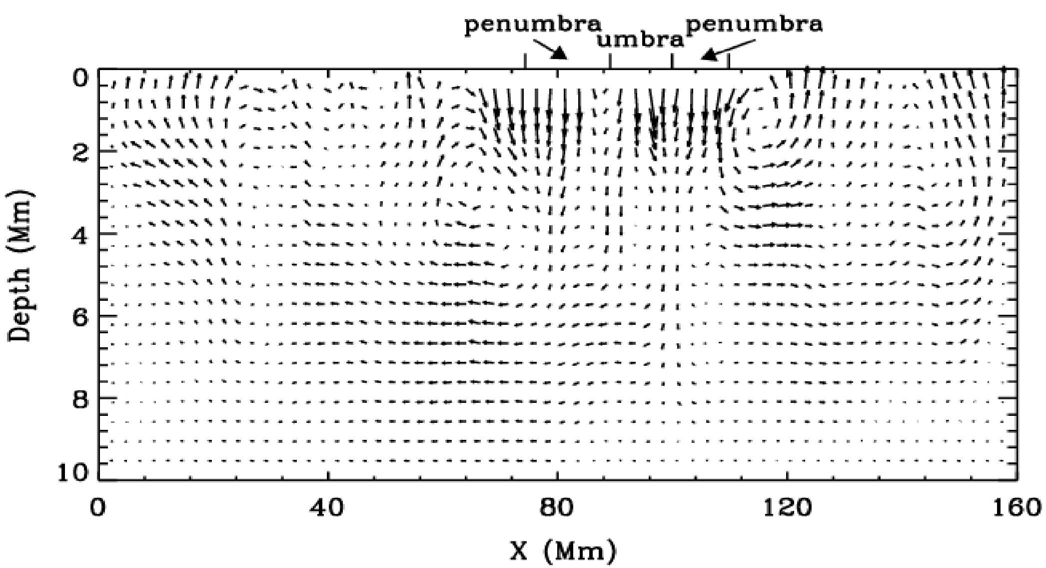
Vertical Subsurface Flow Fields



The subsurface flow structure is basically in agreement with MDI results, but the downward flows are stronger and extend deeper than MDI results. It is AMAZING flow circulation can be seen without use of mass conservation constraint.

Comparing MDI and Hinode Subsurface Flow Fields



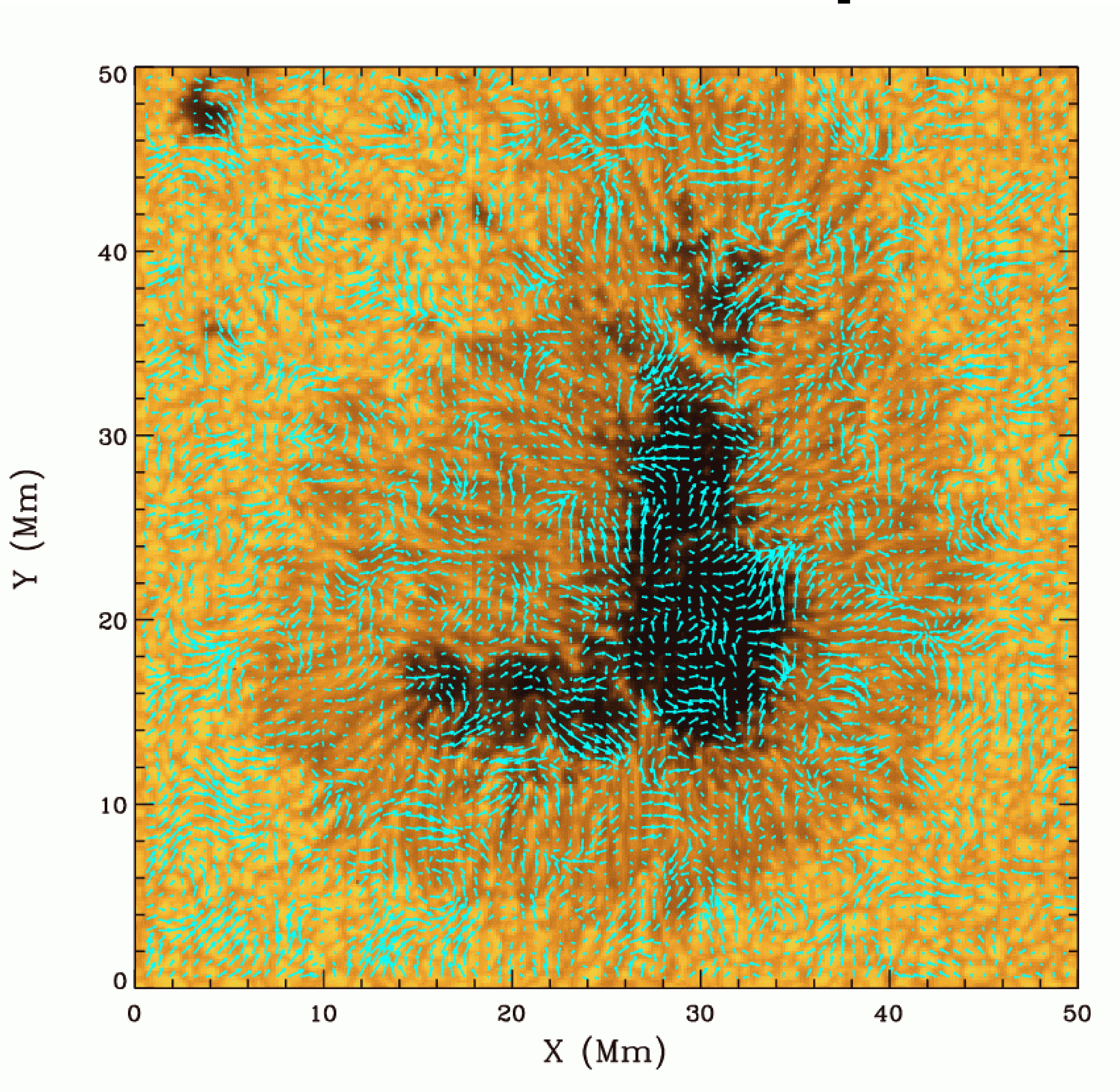


Note that the MDI (above) and Hinode (lower) are from different active regions. Clearly, Hinode results have downflows extending deeper, and have a flow circulation beyond the penumbra area.

All flow fields shown in the previous slides are after some rebinning.

Much better than MDI, Hinode observations enable us to see a lot of fine resolution subsurface flow fields inside the sunspot area.

Fine-Resolution Subsurface Flow Fields inside the Sunspot



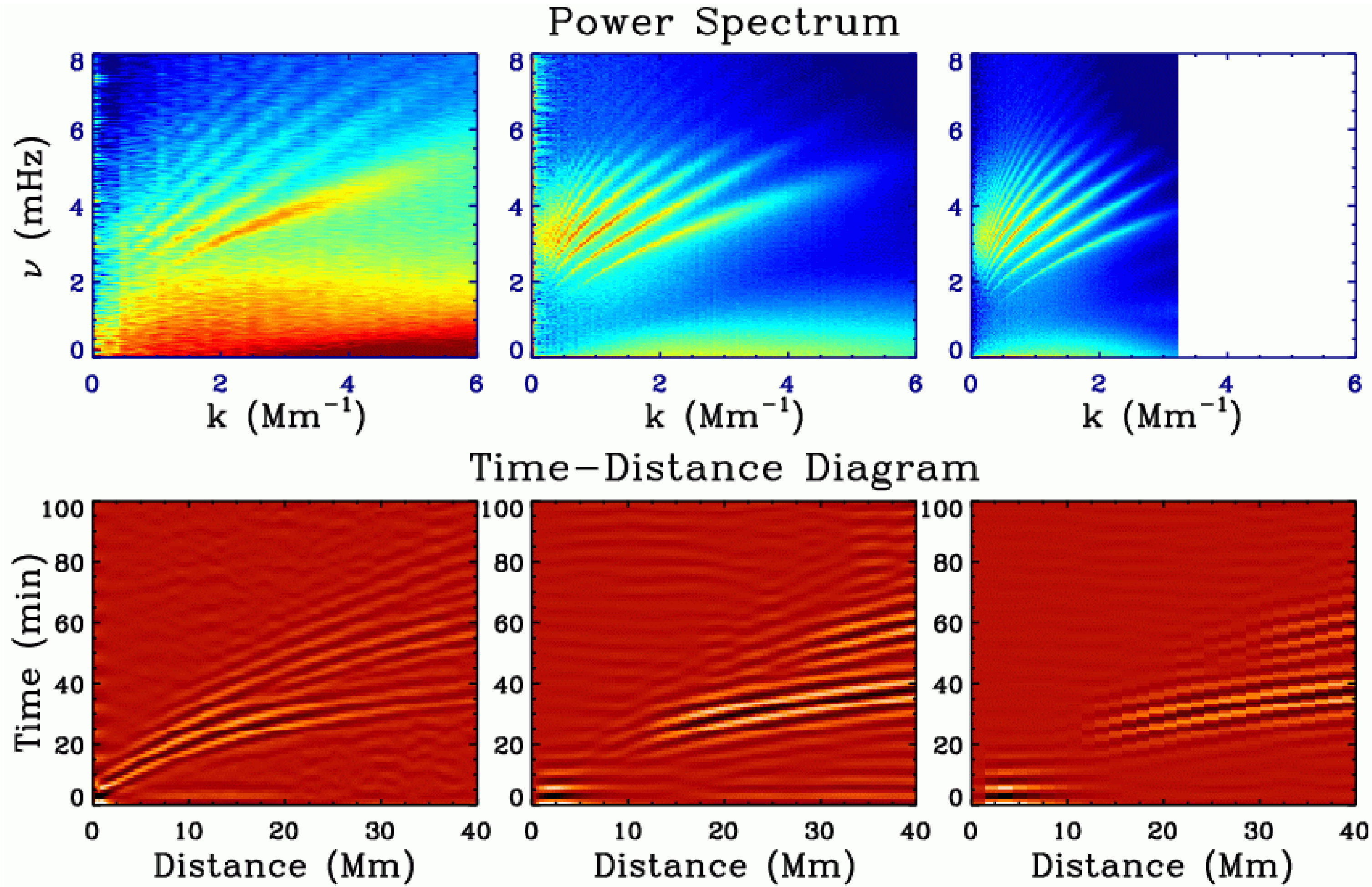
In the past, we face a few difficulties in time-distance helioseismic analysis of active regions, which include the following:

1. The use of phase-speed filtering when performing acoustic travel time measurements may modify acoustic signals inside active regions, hence introduce travel time measurement errors.

2. The use of different filtering, e.g., phase-speed filtering and ridge filtering, may give different measurement results, making measurements hard to interpret.

3. Due to instrument MTF, there are often spurious signals appearing at short distances in time-distance diagram. This makes acoustic travel time measurement of short distances hardly reliable.

Comparing MDI and Hinode Time-Distance Diagrams



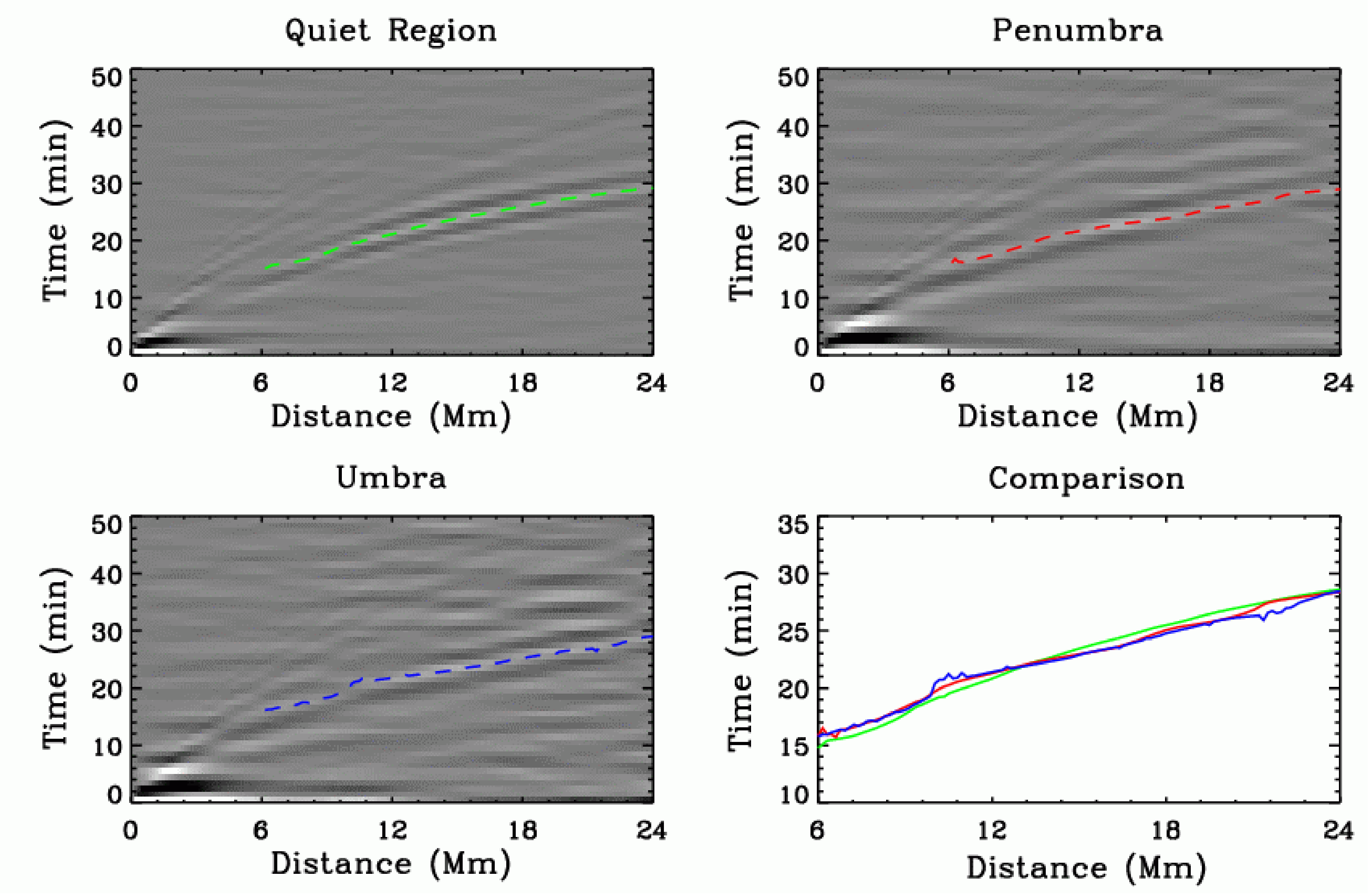
Horizontal stripes at the lower left corner of MDI TD diagram may complicate acoustic travel time measurements in short distances.

As a result, we may be able to perform time-distance helioseismology studies using Hinode observations without applying any filtering, except of course, filtering out convections and f-modes.

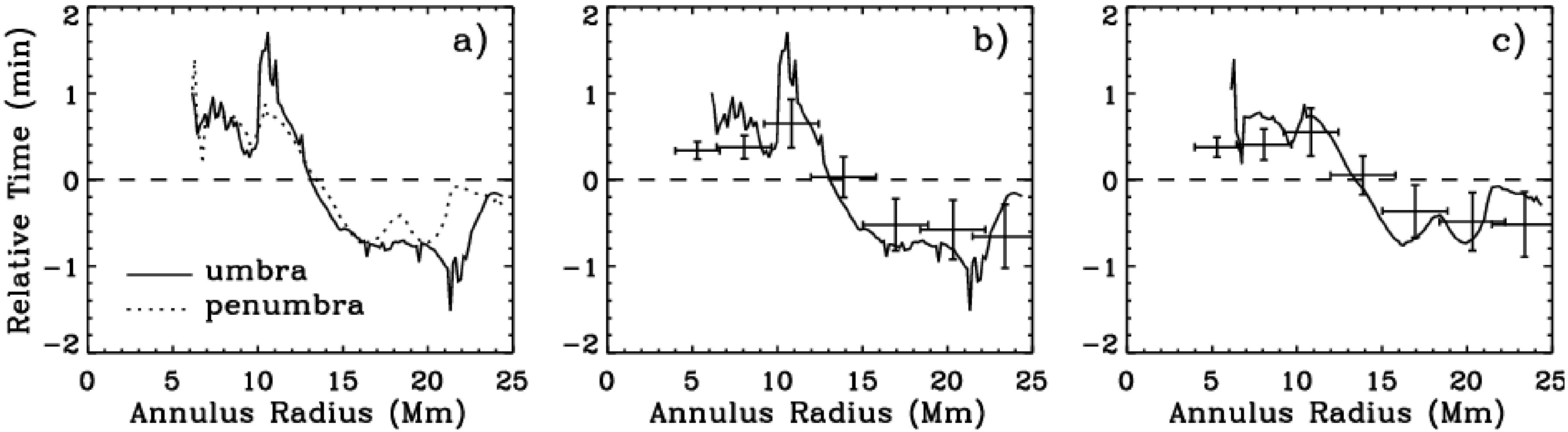
Time-distance diagram is made by cross-correlating acoustic signals located at one central point and signals averaged from annulus around this point.

By selecting the central point located in the quiet Sun, inside sunspot umbra, and penumbra, we can construct three different sets of time-distance diagrams.

Time-Distance Diagrams from Different Regions



Comparing Mean Travel Times

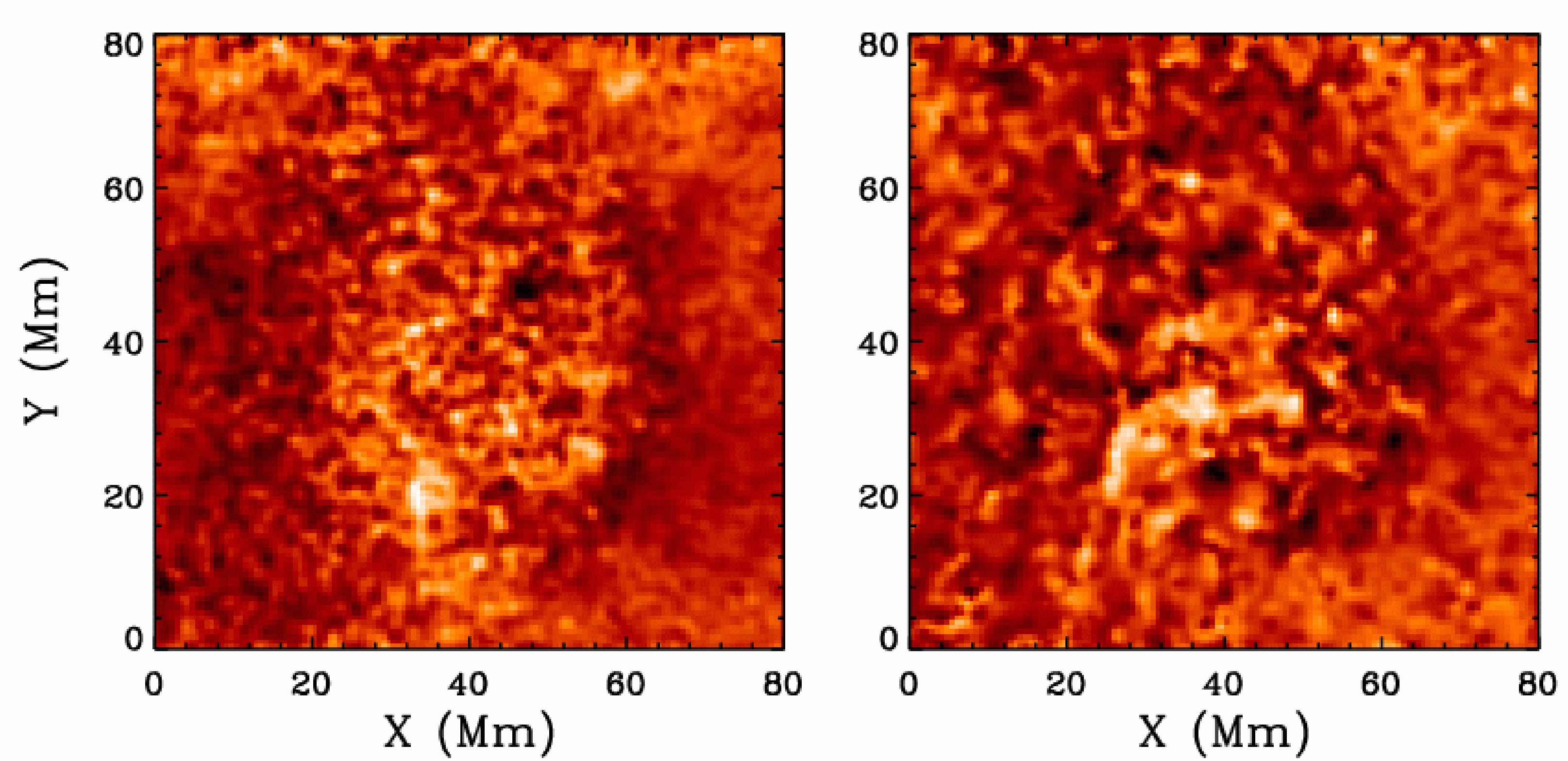


a) Mean travel time variations relative to the quiet Sun. This shows that travel time variations are similar in umbra and in penumbra. b) Solid curve is mean travel time variation in umbra, and data points with error bars are mean travel time variations measured using phase-speed filtering. c) Same as b), but for the penumbra.

Hinode has made measuring travel times inside active regions without using any filtering possible. And it shows that for mean travel times, results are basically consistent using or not using phase-speed filtering, except that using phase-speed filtering would underestimate travel time variations.

This is just 1D analysis, how about 2D maps?

Comparing Mean Travel Time Maps Using and Without Using Phase-Speed Filtering



Left side image is using phase-speed filtering and the right side figure does not have the filtering. It seems there are a lot of similarities as well as discrepancies. More work is certainly needed to better understand this comparison.

Summary

- The subsurface sound-speed structure of active regions derived from Hinode is in good agreement with MDI results.
- The subsurface flow fields are in general agreement with MDI results, but have deeper downward flows. Also, there are mass circulation around penumbra that was not seen in MDI observations.
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- Fine-scale subsurface flows show outflows in the light bridge areas inside sunspot umbra.
- High resolution observation of Hinode has enabled us to do something that is impossible to do using MDI, that is, measuring travel times inside sunspots without applying any filtering. It is found that results are in general agreement with using and without using the filtering.

Subsurface Structures and Flow Fields in the Polar Area

Reserve this Topic for Hinode 3