Center-to-limb variation of acoustic travel times on the Sun

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• Analysis 1 : oscillation power distribution & power spectrum
• Analysis 2 : cross-correlation functions & travel times
  – A. calculate on Postel projection maps
  – B. calculate on the “longitudinal lines”
• Discussions
  – What causes the center-to-limb variation?
    • difference in the formation height?
    • foreshortening effect?
## Dataset

<table>
<thead>
<tr>
<th></th>
<th>Hinode/SOT</th>
<th>SDO/HMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>observable</td>
<td>Ca II H line intensity</td>
<td>Dopplergram &amp; continuum intensity</td>
</tr>
<tr>
<td>pixel scale</td>
<td>0.218 arcsec (can be smaller)</td>
<td>0.5 arcsec</td>
</tr>
<tr>
<td>cadence</td>
<td>1 min</td>
<td>45 sec</td>
</tr>
<tr>
<td>observation length</td>
<td>12-16 hrs (&lt;24 hr)</td>
<td>12-24 hrs (or more)</td>
</tr>
<tr>
<td>FOV</td>
<td>see Figure</td>
<td>full disk (-&gt; used cut-out)</td>
</tr>
</tbody>
</table>

SOT field of view

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- North Pole
- East Limb
- Disk Center
- South Pole

Full disk (full disk)
Analysis 1

Center-to-limb variation of oscillation power distribution & power spectrum
Power distributions

HMI intensity
HMI Dopplergram
SOT Ca II H intensity
Power distributions

• Generally, the power decreases as the distance from the disk center increases.
  – Above the acoustic cutoff frequency the Dopplershift oscillation power behaves differently.
SOT Ca II H intensity oscillation power spectra (at angular degree l=687)

- Disk center
- East limb
- South pole
- North pole

components with weaker power
HMI power spectrum (at North polar regions)

HMI Dopplergram

HMI intensity

North & South

North & South
Power Spectrum

• SOT: The power of the waves traveling toward the disk center is smaller than the others at the limb/polar regions
• HMI: The power of northward and southward wave components are smaller than the others at the north polar region.
• Power reduction rate depends on frequency
• Line asymmetry?
Analysis 2

Center-to-limb variations of Cross-correlation functions & travel times
SOT Ca II H intensity
Cross-correlation functions
(distance=1.2deg)

Disk center

West
North
East
South

weakest: West
East limb

weakest: North
South pole

weakest: South
North pole

Anisotropy in amplitude
• consistent with power spectrum

components with weaker power (SOT)
HMI cross-correlation functions (distance = 1.2deg)

HMI Dopplergram

HMI intensity

Anisotropy in amplitude
• Both South and North components are weaker.
HMI Dopplergram cross-correlation function

distance=1.2deg

North polar regions
HMI intensity cross-correlation function

distance=1.2deg

North polar regions
Analysis 2B:
Calculate the cross-correlation on the rotated longitudinal line in the equator region
(SDO/HMI datasets are used)

no tracking
no phase-speed filtering
w/o Postel projection
cross-correlation functions (distance=1deg)

-5 deg

-15 deg

-25 deg

-35 deg

-45 deg

-55 deg

-65 deg

“longitude”
cross-correlation functions (distance=1deg)

the shift is not parallel

Westward & Eastward

-5 deg

-15 deg

-25 deg

-35 deg

-45 deg

-55 deg

-65 deg

“longitude”
Gabor-wavelet fitting

cf. Kosovichev & Duvall 1997

\[ G(\tau) = a_0 \exp\left(-a_1 (\tau - a_2)^2\right) \sin(a_3 (\tau - a_4)) \]

Group travel time
frequency
Phase travel time (zero-crossing point)

short    long
Phase travel times depend on the longitude.

Phase travel times depend on the definition...
Sun rotates toward west
- \( t(\text{west}) - t(\text{east}) \) should be negative, but...

the sign depends on definition... (as known)
But in any case, they also depend on \textit{longitude}.
Group travel times

t(west) - t(east) are negative
Gabor wavelet fitting results frequency

East/West difference: due to rotation
Dependence on longitude:

HMI Dopplergram

Intensity

-60 deg longitude (close to East limb)

EQUATOR

+60 deg longitude (close to West limb)
For further study...

• Rotation speed (~2km/s) is too large
  – tracking is needed?
• The cross-correlation functions are too noisy
  – especially for the larger distance cases, for the intensity dataset cases.
  – some kind of filtering is needed?
  – (since we do not use Cartesian coordinate, filtering is not so straight-forward, though)
Discussions

• What causes the difference of the properties in the polar regions?
  1. Difference of the formation height?
  2. Foreshortening effect?
  3. Some other effect we did not know of...?
1. Difference of formation height?

- When we observe the limb regions, the formation height is relatively higher.

- This may affect the helioseismology measurements in several ways.
  - the signals we cross correlate with may be come from different layers in the atmosphere
  - the effective distance of the observed wave signal may be modified

- We are investigating this effect by using numerical simulation of wavefields in different height layers.
2. Foreshortening effect

**mimic polar dataset (SOT)**

By reducing the resolution of a dataset observed at the disk center, we produced a “mimic” polar dataset.

This is an example of mimic “N80-deg latitude” power spectrum and the cross correlation function.

Amplitudes of both northward/southward are reduced by this (foreshortening) effect only.
Summary

• Oscillation power decreases toward the limb
  – Toward-the-limb components are weaker (SOT)
  – Toward-the-limb and from-the-limb components are weaker (HMI I&V)

• Cross-correlation functions and fitting parameters of them show dependence on the location on the disk
  – “shift” is somewhat complicated -> need careful considerations

• What kind of effect do we forget in interpretation?
  – Formation height issue, foreshortening effect, .....?
Motivation

• We are investigating the dynamics of high-latitude regions of the Sun using the high-resolution Hinode/SOT observation datasets.
  – North-South supergranular-cell alignments [Nagashima et al. (2011) ]
  – Meridional flow / rotation flow profiles [ongoing]
• Since the field of view of SOT is limited, combining the SOT high-resolution observations with HMI full-disk observations provides us a good opportunity to investigate the dynamics in more detail.
• We compare the basic properties of SOT and HMI datasets.
Dataset 1: SOT

- Solar Optical Telescope (SOT) onboard Hinode
  - Ca II H line intensity maps (running-difference taken)
  - 0.218 arcsec / pixel
  - 1-min cadence
  - Disk center, East limb, North/South polar regions
  - Observed the polar regions when the B0 angle was largest (March for the South, September for the North)
Observations and data reduction (2/2)

- Helioseismic and Magnetic Imager (HMI) onboard SDO
  - Dopplergrams/ continuum intensity (running-difference taken)
  - 0.5 arcsec / pixel
  - 45-sec cadence
  - Full-disc observation -> used cut-out

1. Tracked the images
2. Projected the images into the heliographic coordinates by using Postel’s projection
3. Calculated power, power spectrum, and cross-correlation functions
HMI Dopplergram power spectrum (at different latitudes in North polar regions)
HMI intensity power spectrum (North polar regions)
Couvidat & Birch 2009

Figure 1 (part)

- the shift due to the flow is not parallel
“Travel time” measured above the “surface”

- “Travel time” of acoustic waves is defined as the time interval where the cross-correlation function is strong.
- Estimating the travel time from the ray path in the left figure is NOT correct, because above the “surface” the dominant wave components are evanescent [Nagashima et al. 2009]
Correct ray path

From Lower to Upper

From Upper to Lower

**evanescent region**

<table>
<thead>
<tr>
<th>from</th>
<th>to</th>
<th>equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>lower layer</td>
<td>lower layer</td>
<td>$t_{A\rightarrow B} = t_p$</td>
</tr>
<tr>
<td>upper layer</td>
<td>upper layer</td>
<td>$t_{A'\rightarrow B'} = t_p$</td>
</tr>
<tr>
<td>lower layer</td>
<td>upper layer</td>
<td>$t_{A\rightarrow B'} = t_p + t_a$</td>
</tr>
<tr>
<td>upper layer</td>
<td>lower layer</td>
<td>$t_{B'\rightarrow A} = t_p - t_a$</td>
</tr>
</tbody>
</table>