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

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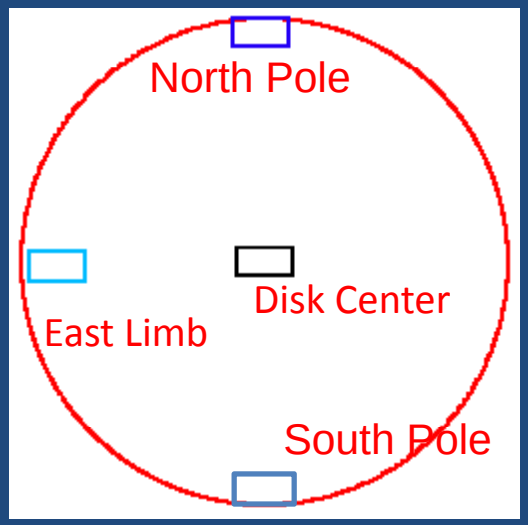
  - B. calculate on the “longitudinal lines”
- Discussions
  - What causes the center-to-limb variation?
    - difference in the formation height?
    - foreshortening effect?

Dataset

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

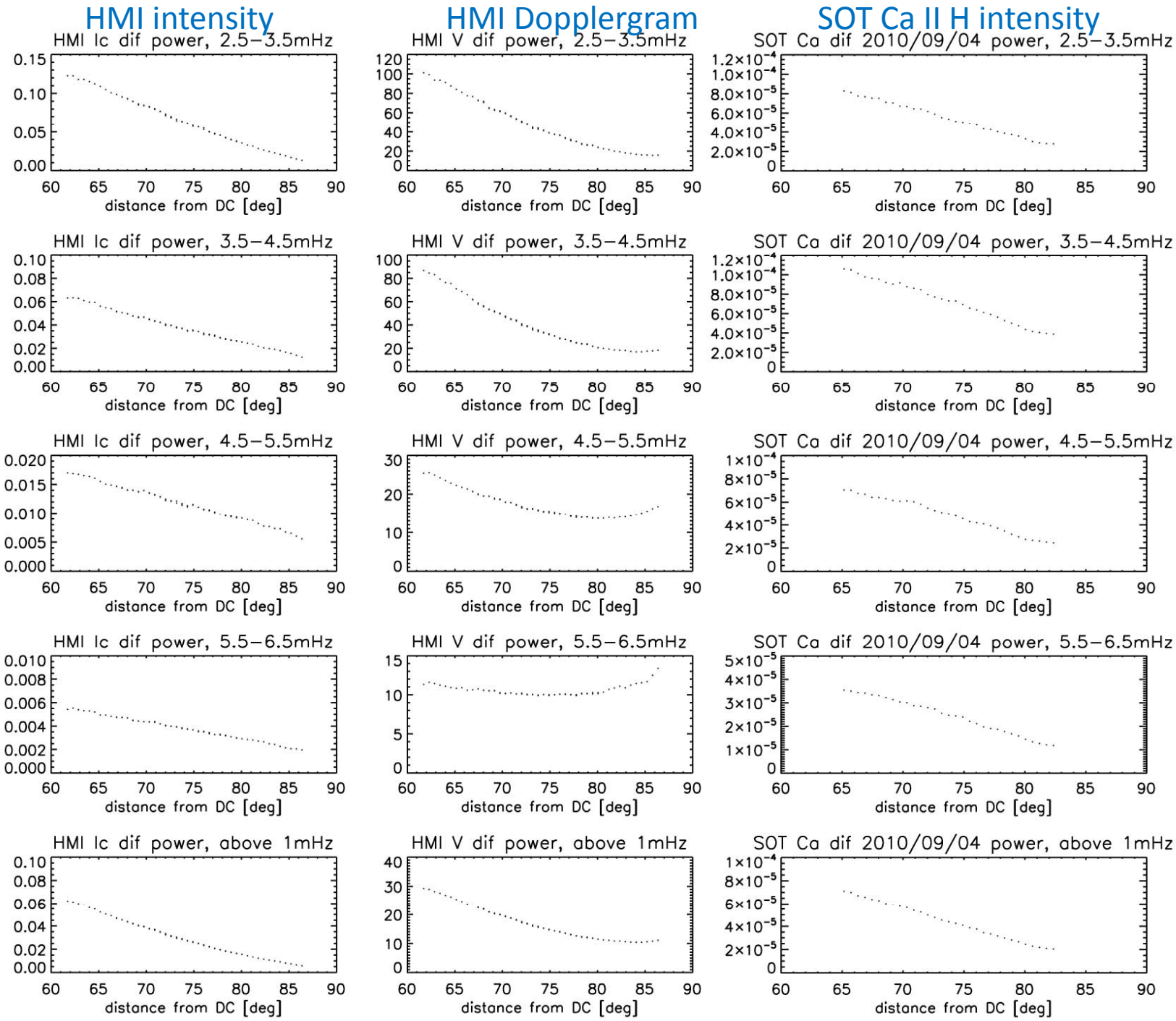


SOT field of view

Analysis 1

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

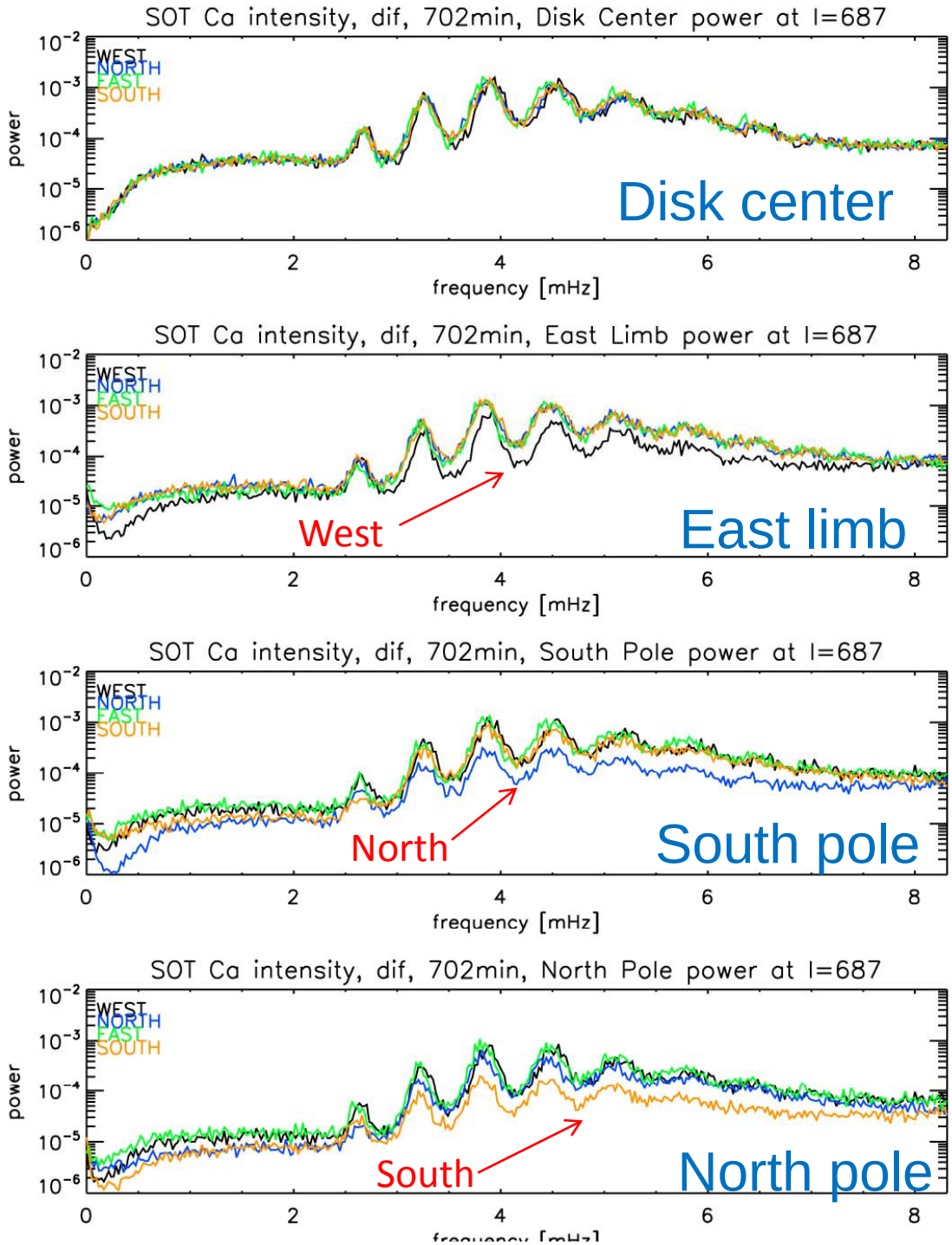
Power distributions



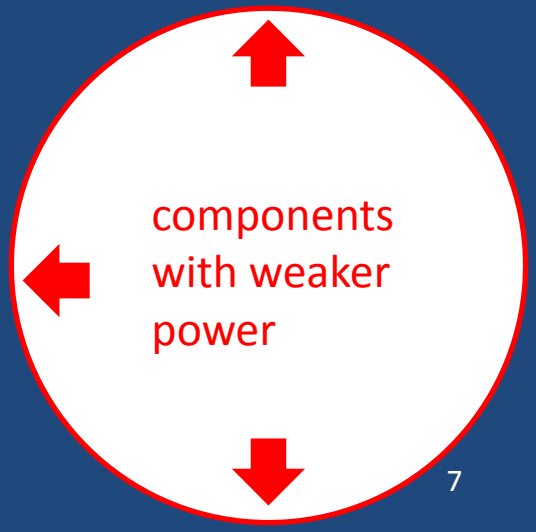
Power distributions

- Generally, the power decreases as the distance from the disk center increases.
  - Above the acoustic cutoff frequency the Dopplershift oscillation power behaves differently.

Power spectrum



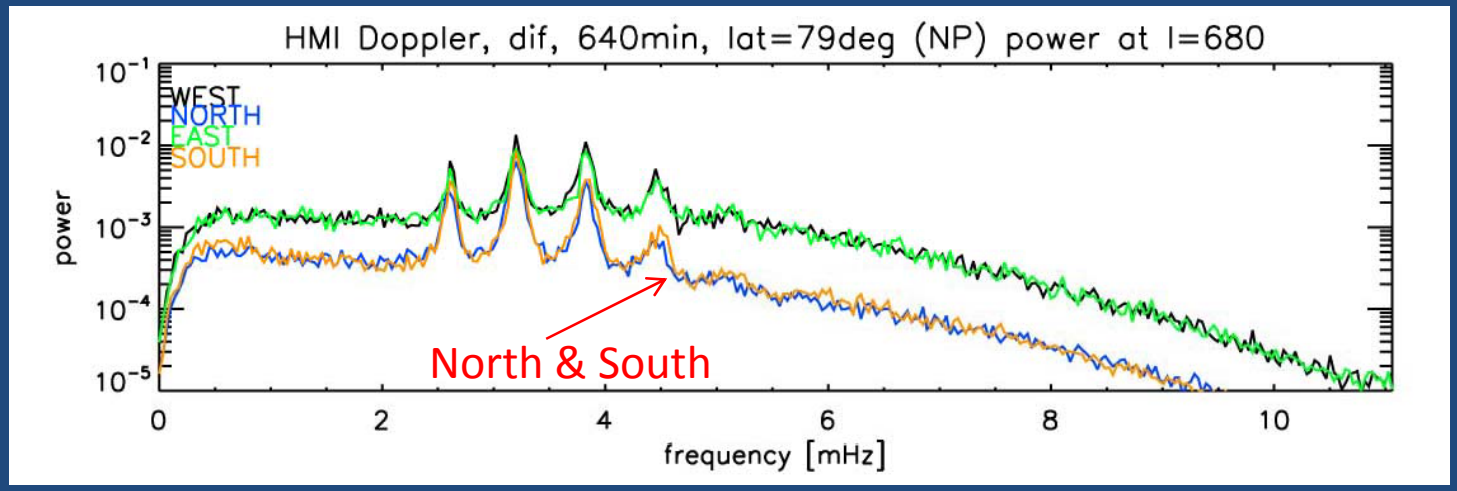
SOT Ca II H intensity oscillation power spectra (at angular degree l=687)



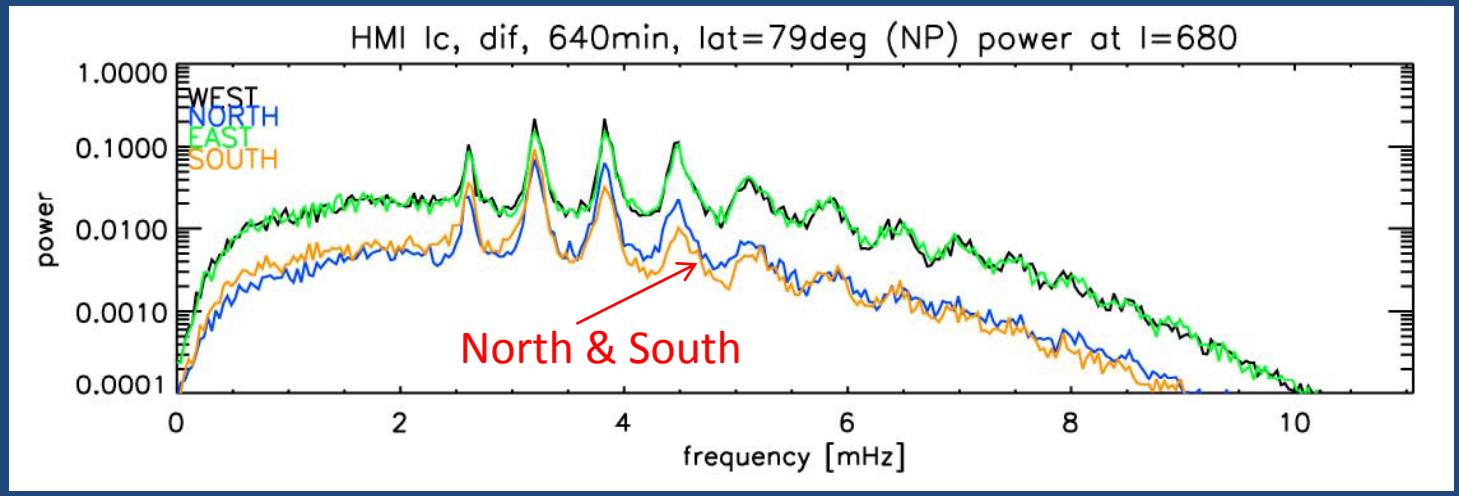
Power spectrum

HMI power spectrum (at North polar regions)

HMI Dopplergram



HMI intensity

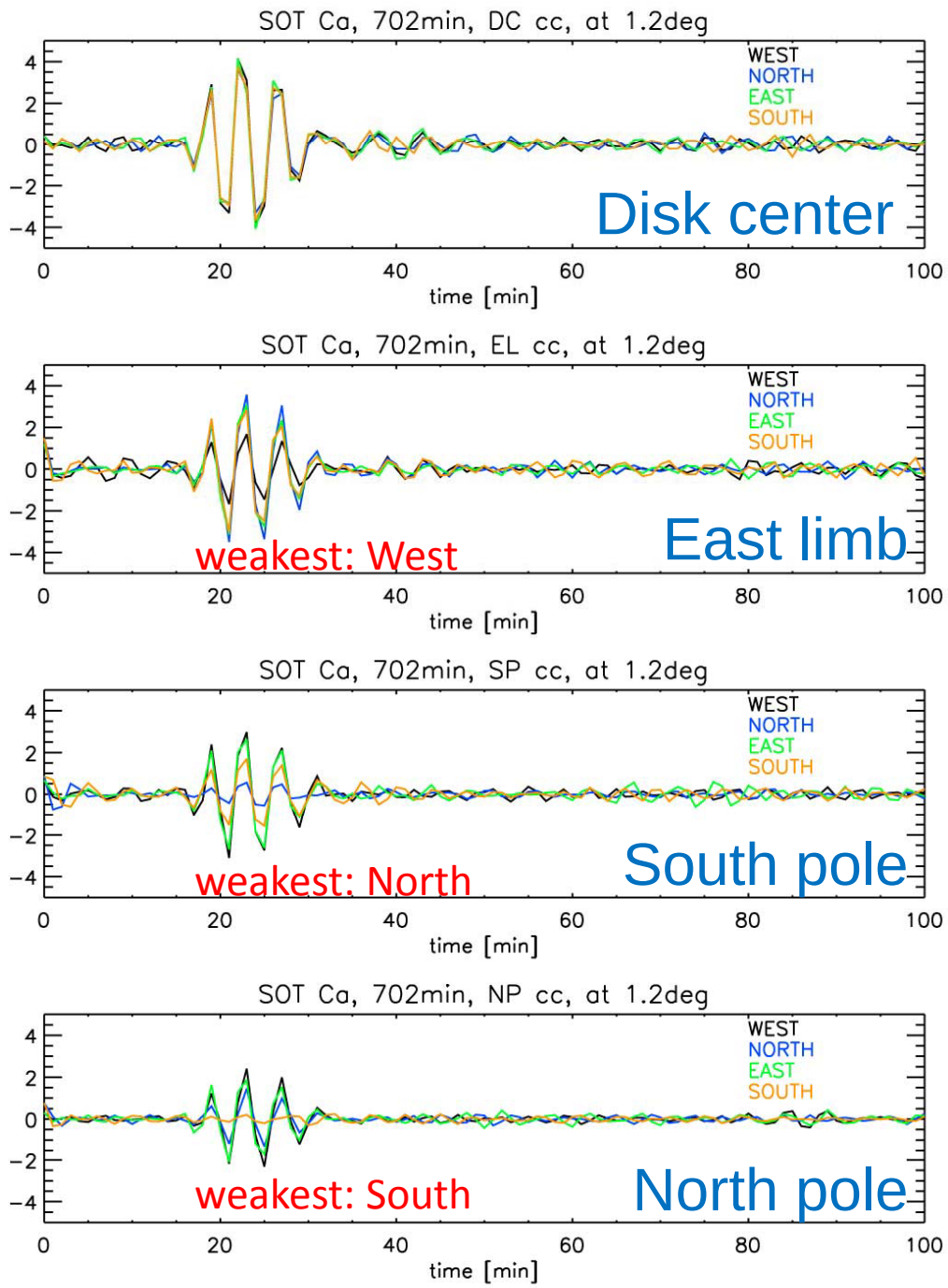


Power Spectrum

- 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

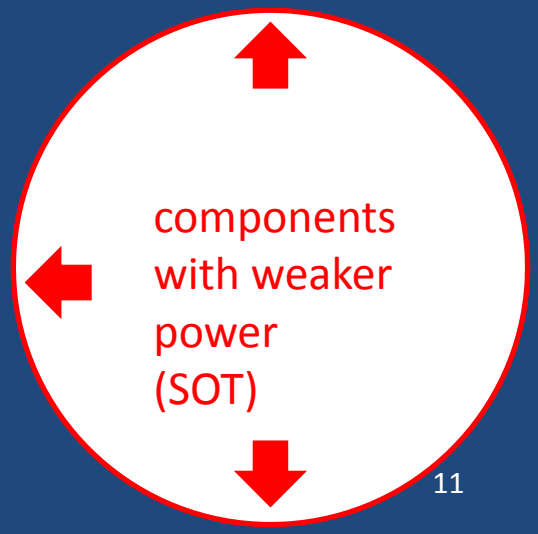


SOT Ca II H intensity Cross-correlation functions (distance=1.2deg)

West
North
East
South

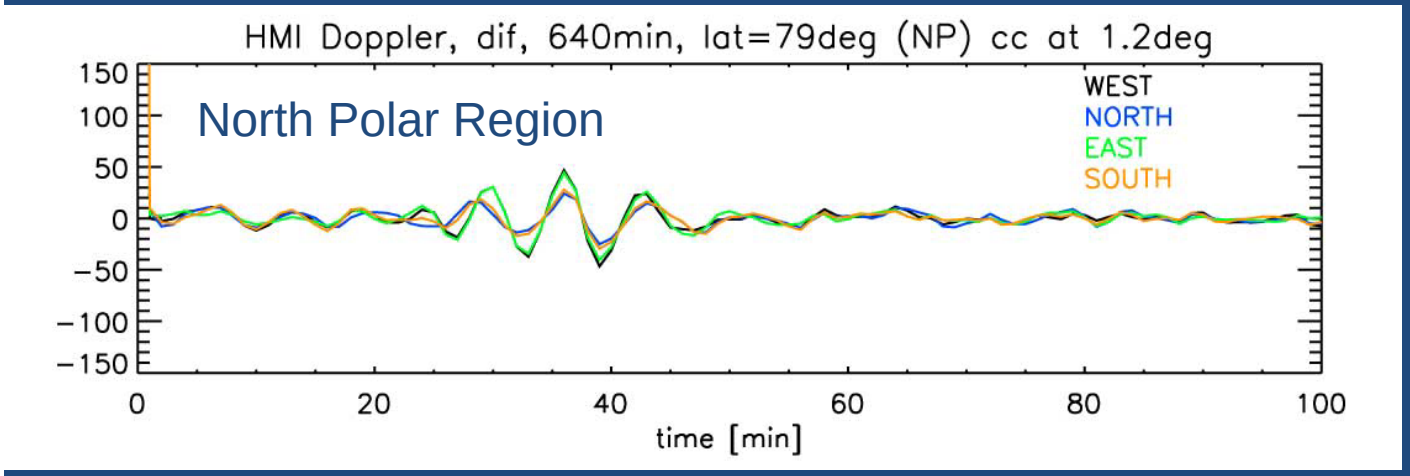
Anisotropy in amplitude

- consistent with power spectrum

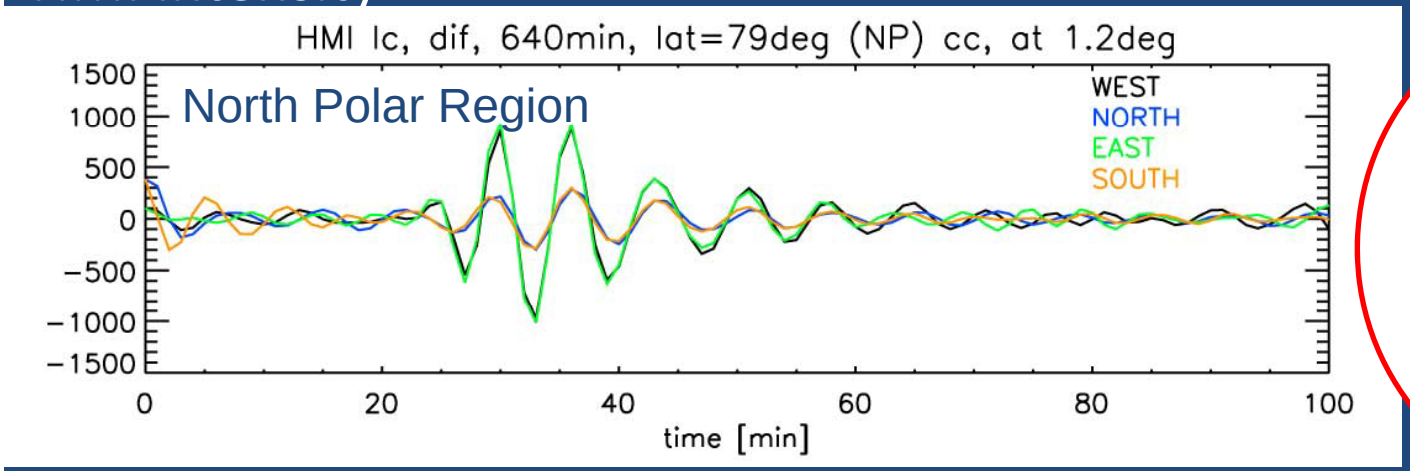


HMI cross-correlation functions (distance =1.2deg)

HMI Dopplergram



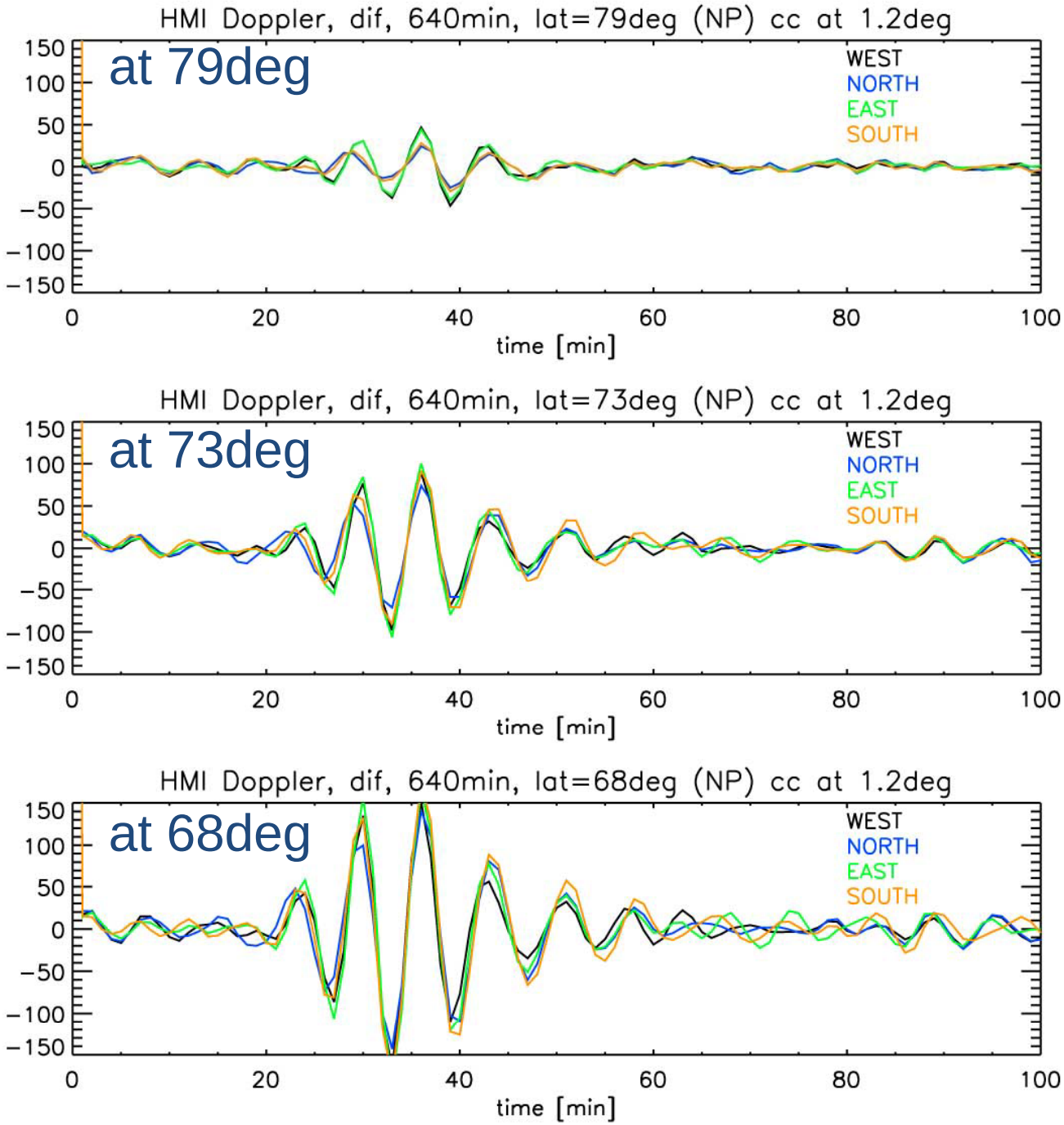
HMI intensity



components with weaker power (HMI V & I)

Anisotropy in amplitude

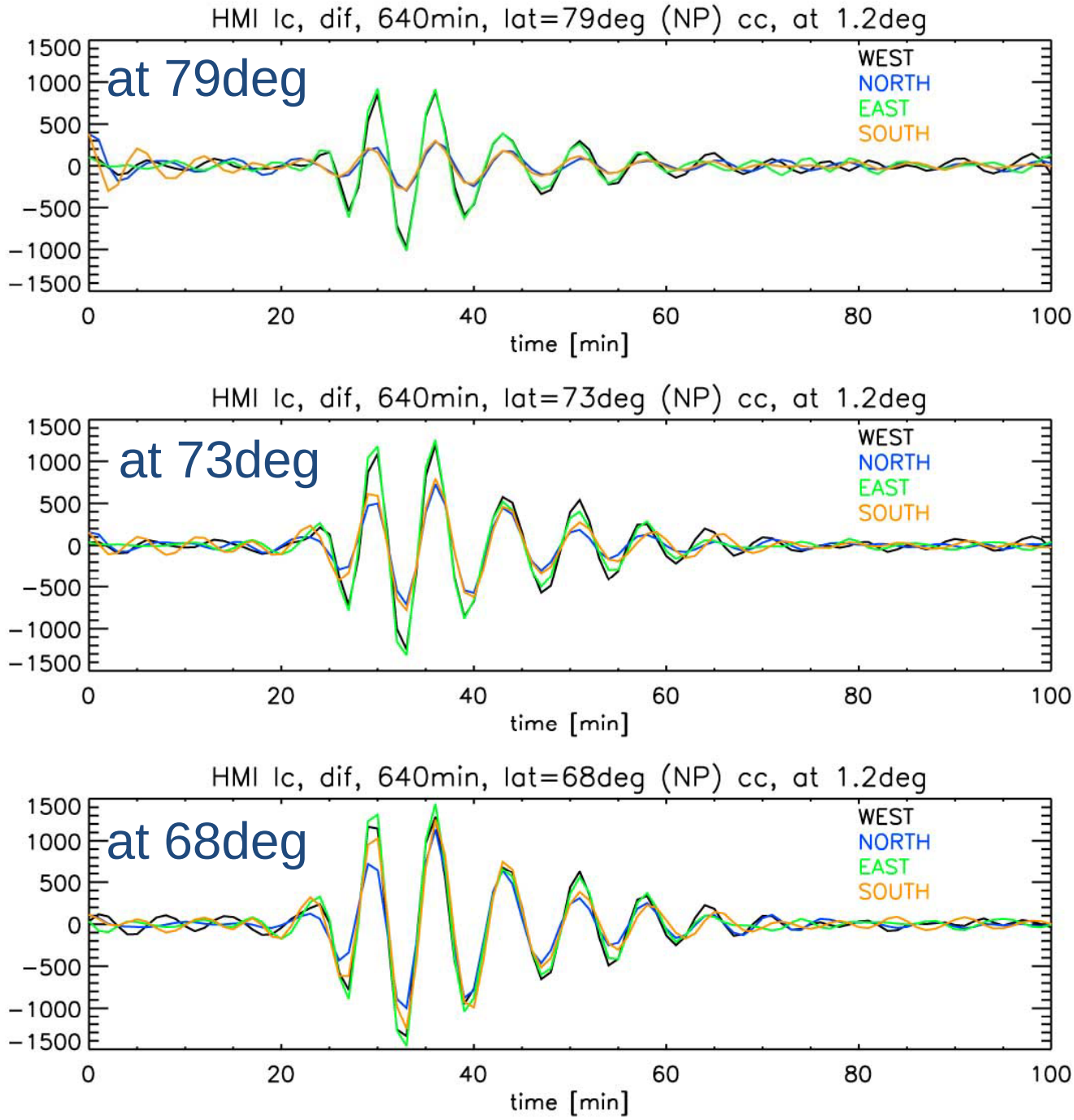
- Both South and North components are weaker.



HMI Dopplergram cross-correlation function

distance=1.2deg

North polar regions



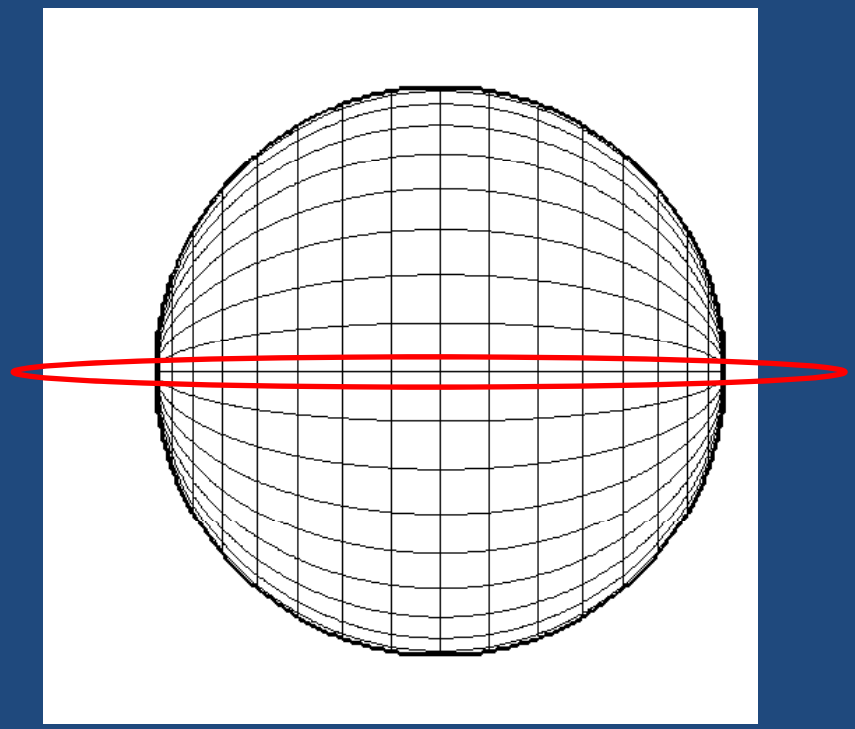
HMI <u>intensity</u> cross-correlation function

distance=1.2deg

North polar regions

Analysis 2B:
Calculate the cross-correlation on the rotated longitudinal line in the equator region

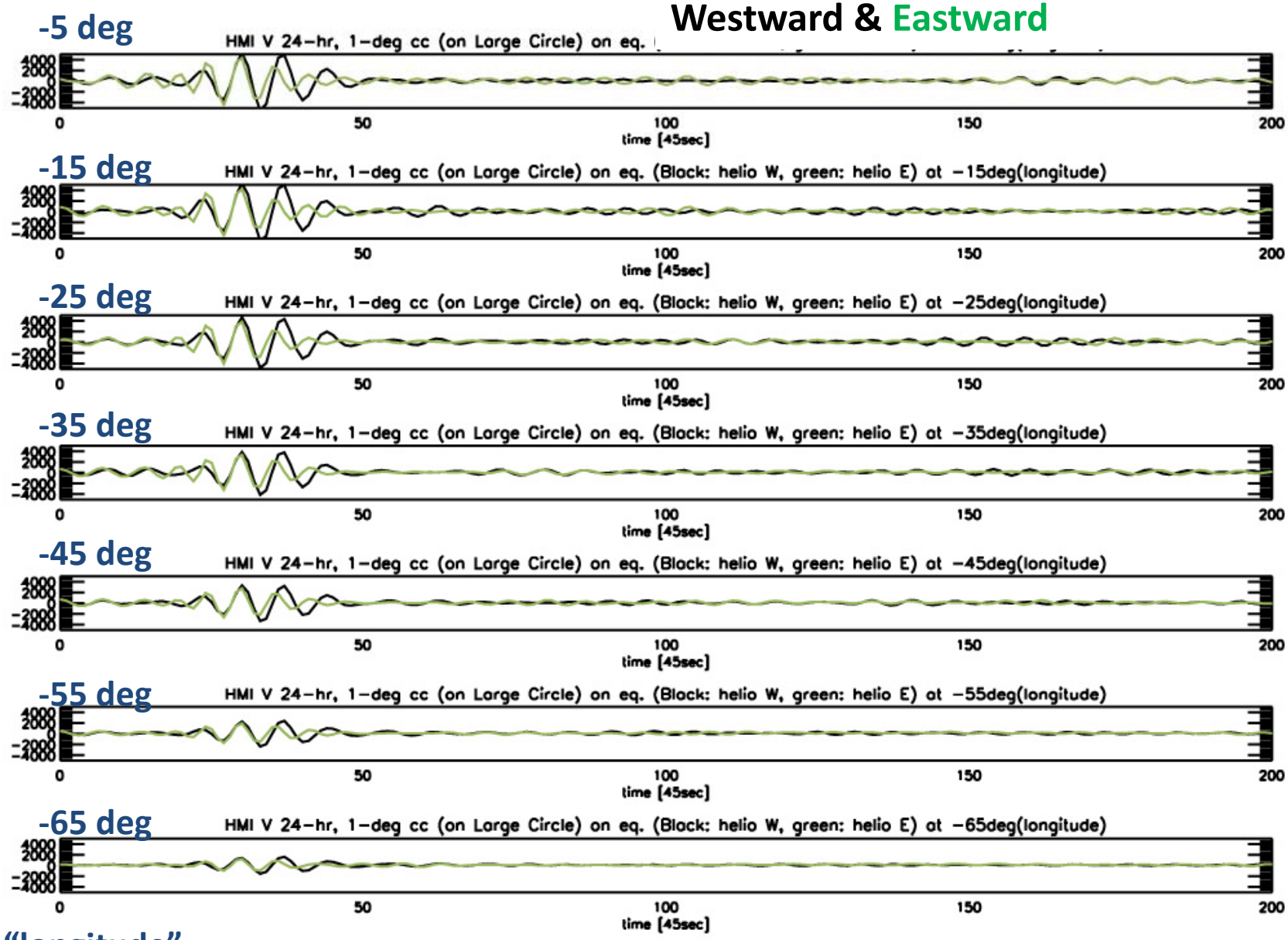
(SDO/HMI datasets are used)



no tracking
no phase-speed filtering
w/o Postel projection

cross-correlation functions (distance=1deg)

Westward & Eastward



amplitude

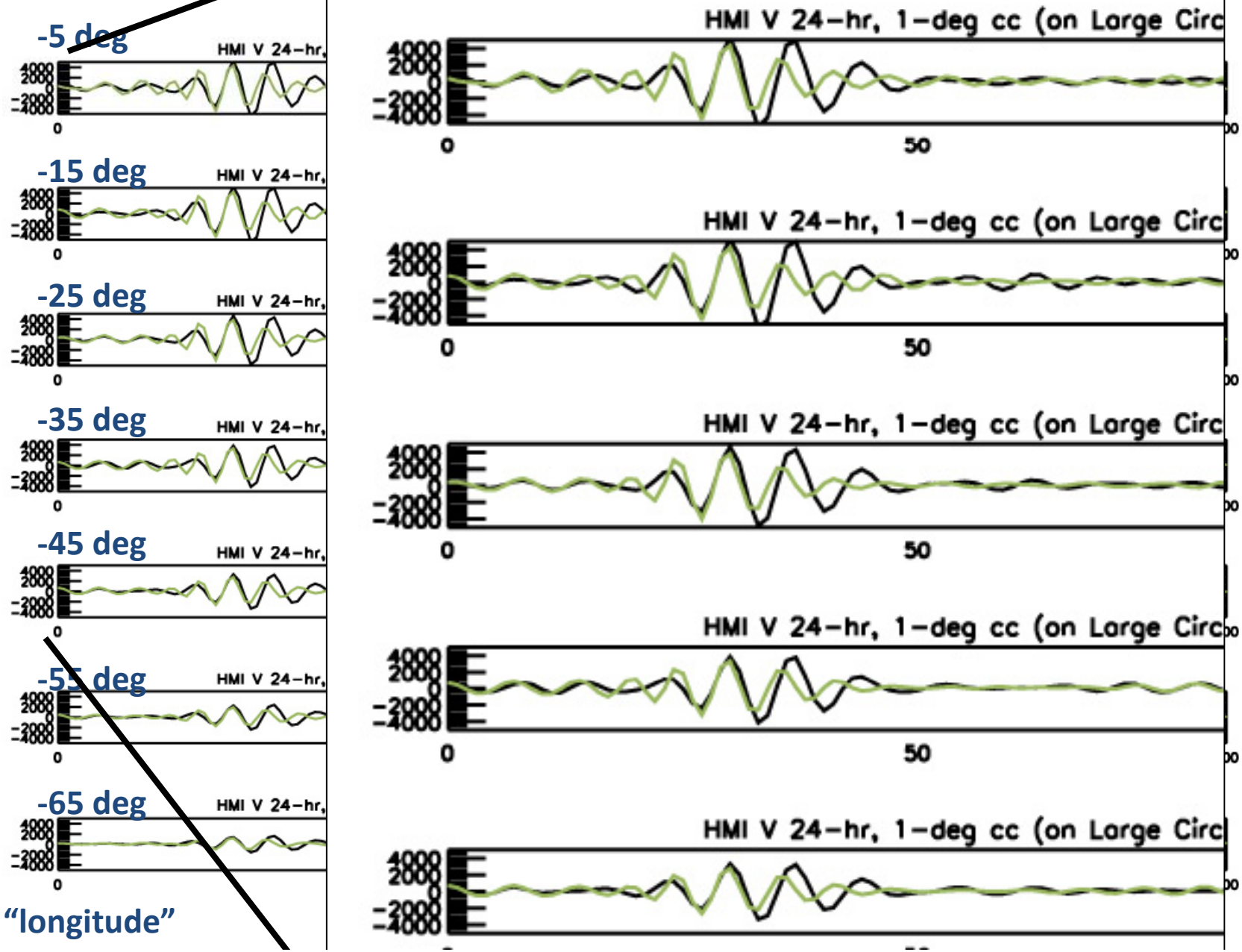
smaller

"longitude"

cross-co deg)

Westward & Eastward

the shift is not parallel



"longitude"

Gabor-wavelet fitting

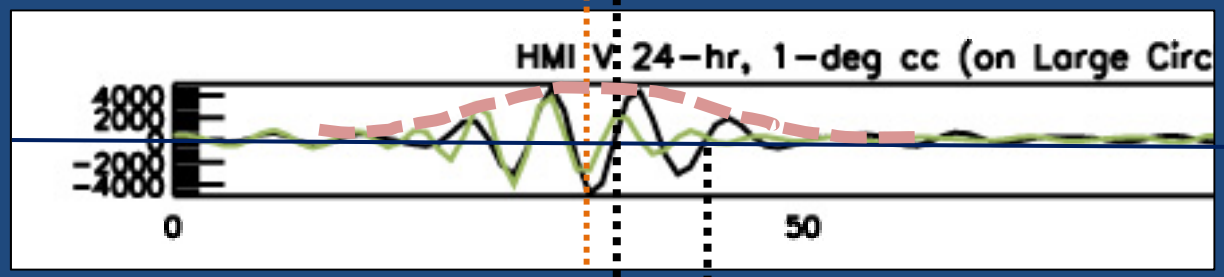
cf. Kosovichev & Duvall 1997

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

Group travel time

frequency

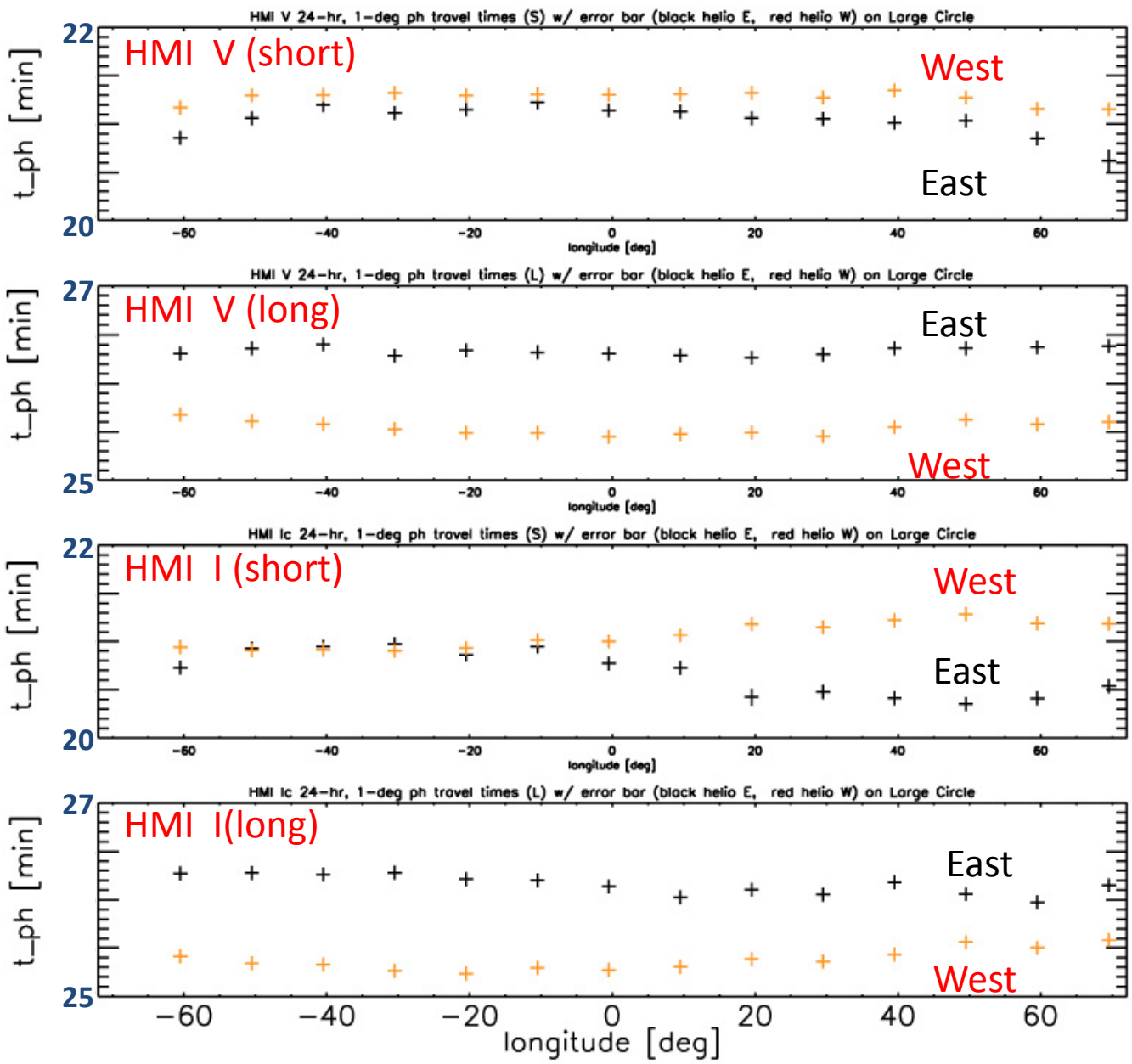
Phase travel time
(zero-crossing point)

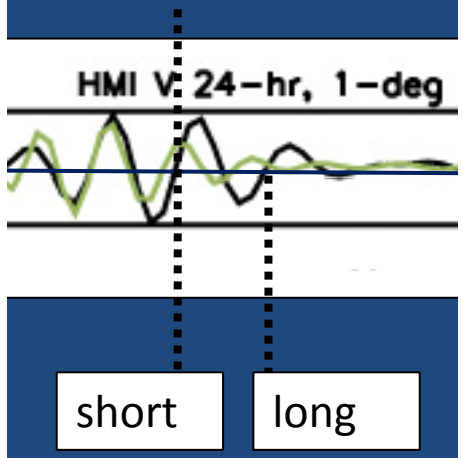


short

long

Phase travel times



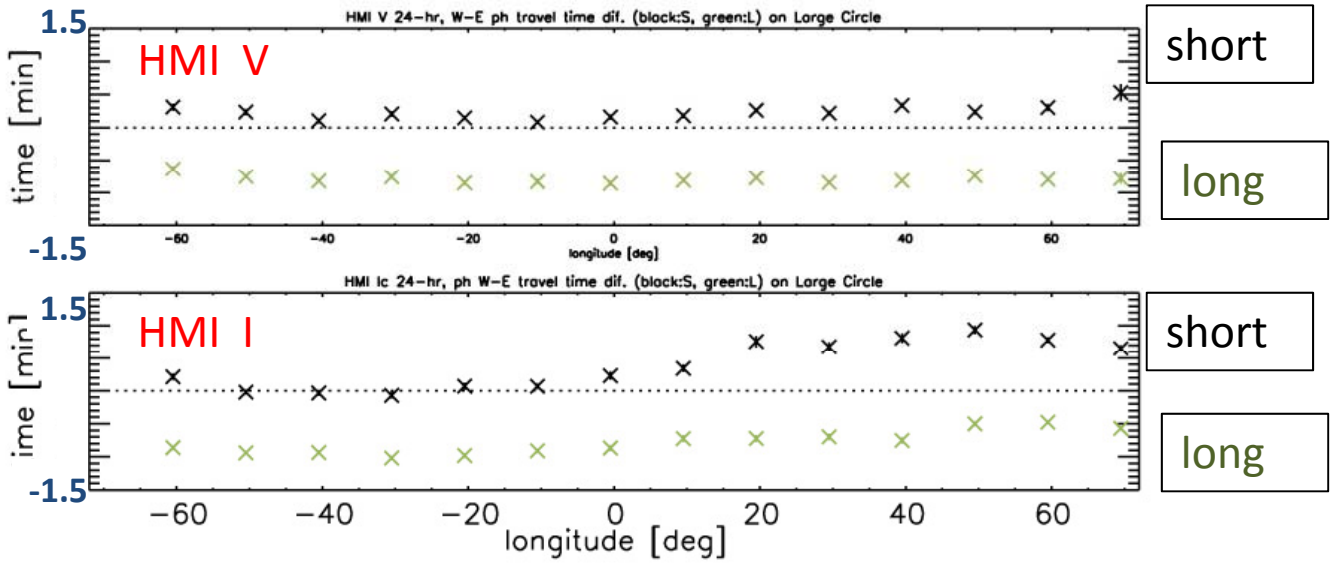


Phase travel times depend on the longitude.

Phase travel times depend on the definition…

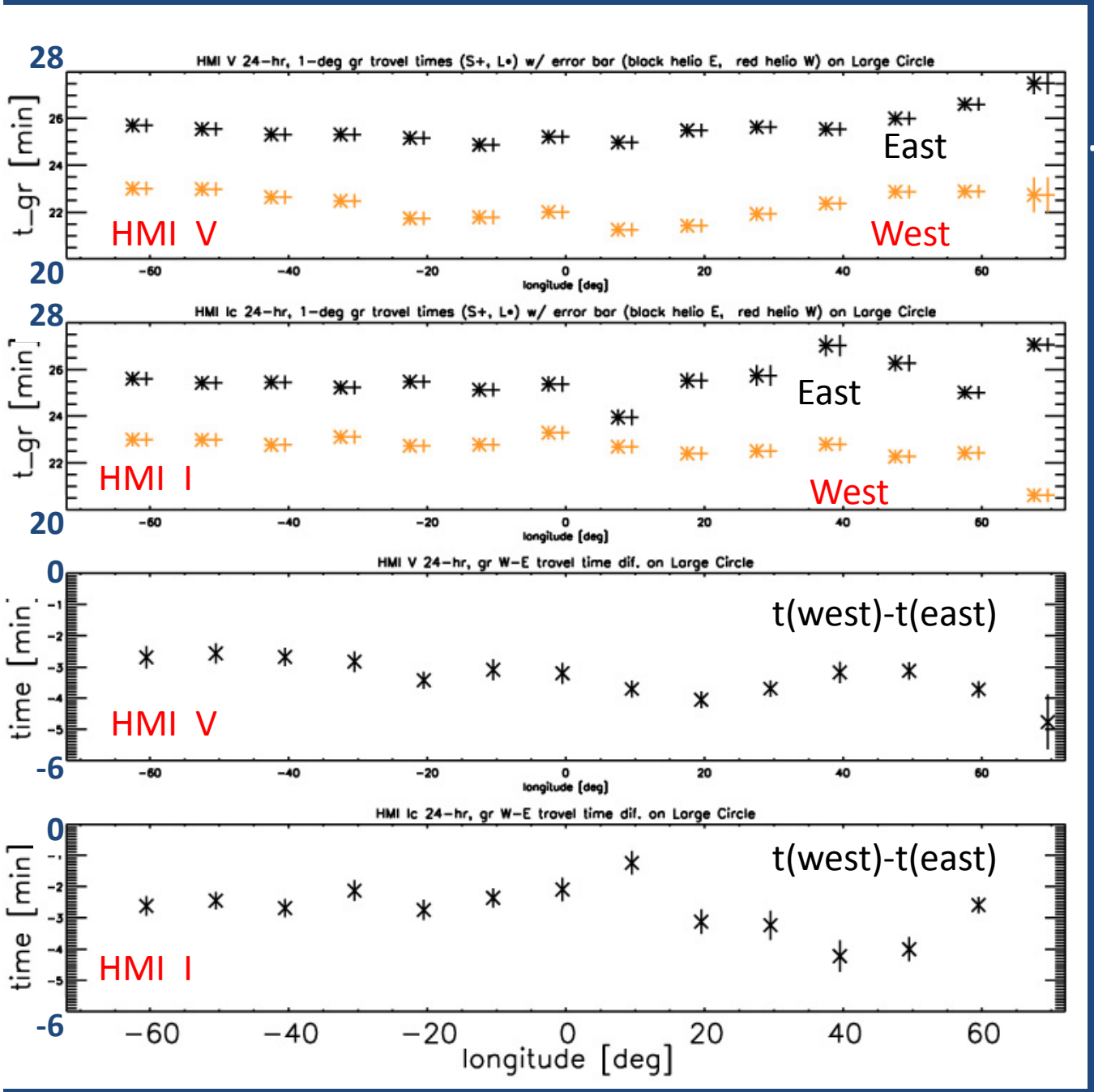
West-East phase travel time difference

Sun rotates toward west
-> t(west)-t(east) should be negative,
but…



the sign depends on definition… (as known)
But in any case, they also depend on *longitude*.

Group travel times

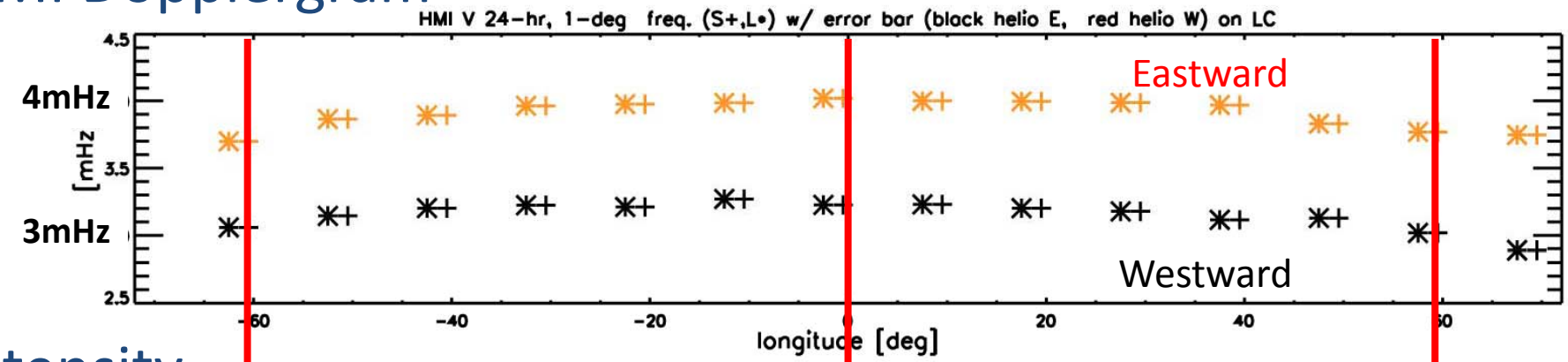


t(west)-t(east) are negative

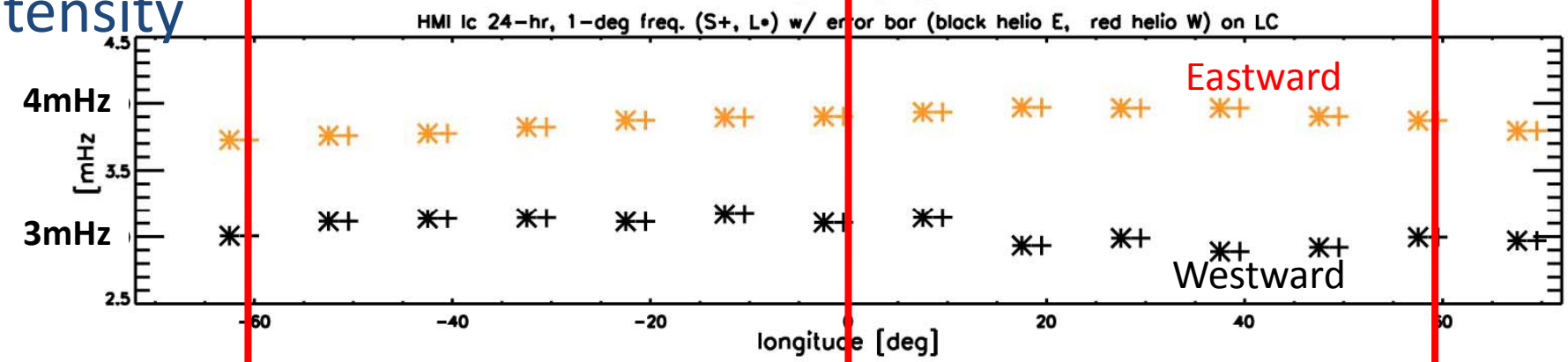
Gabor wavelet fitting results frequency

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?

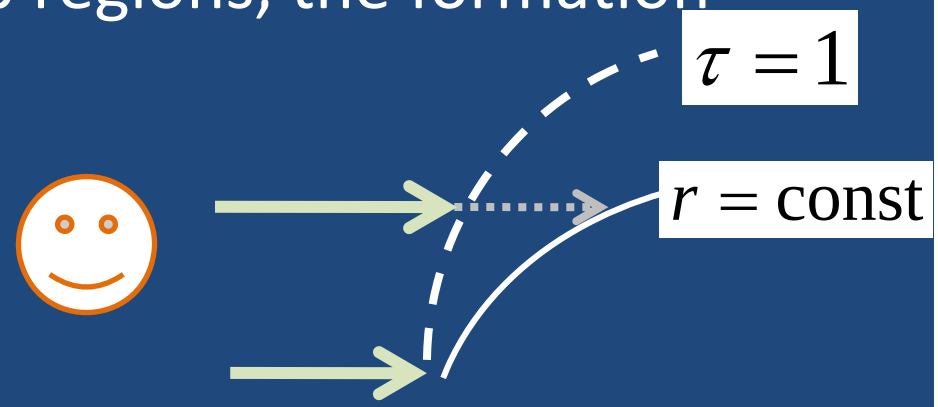
  - (since we do not use Cartesian coordinate, filtering is not so straight-forward, though)

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.



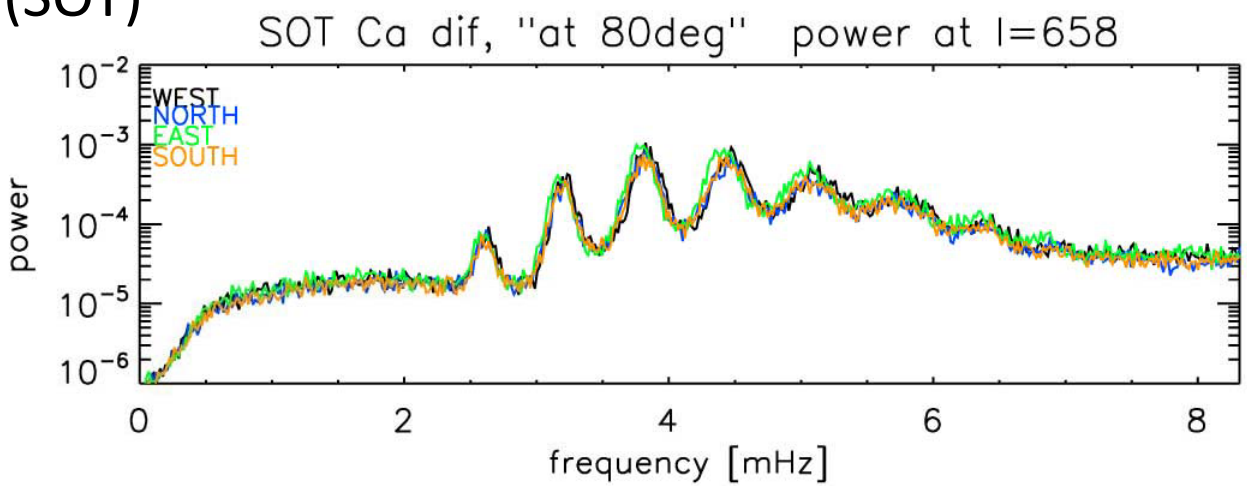
- This may affect the helioseismology measurements in several ways.
  - the signals we cross correlate with may be come from different layers in the atmosphere
  - the effective distance of the observed wave signal may be modified
- We are investigating this effect by using numerical simulation of wavefields in different height layers.

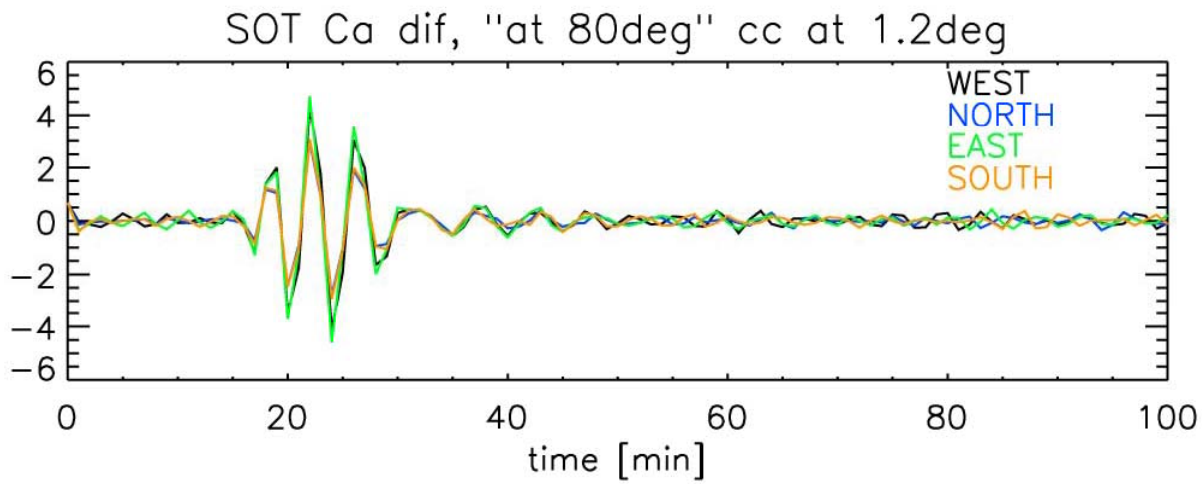
2. Foreshortening effect

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

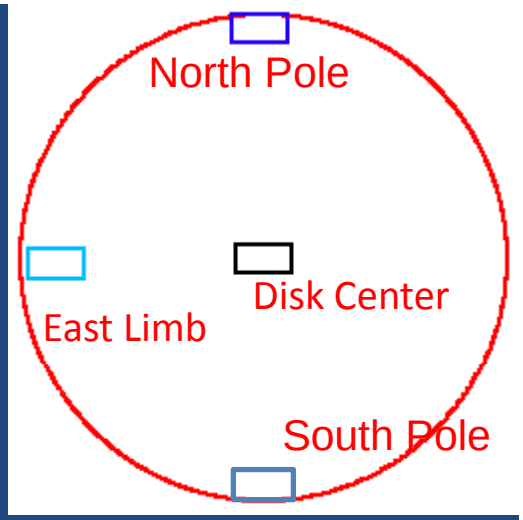
- Oscillation power decreases toward the limb
  - Toward-the-limb components are weaker (SOT)
  - Toward-the-limb and from-the-limb components are weaker (HMI I&V)
- Cross-correlation functions and fitting parameters of them show dependence on the location on the disk
  - “shift” is somewhat complicated -> 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)



SOT field of view

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

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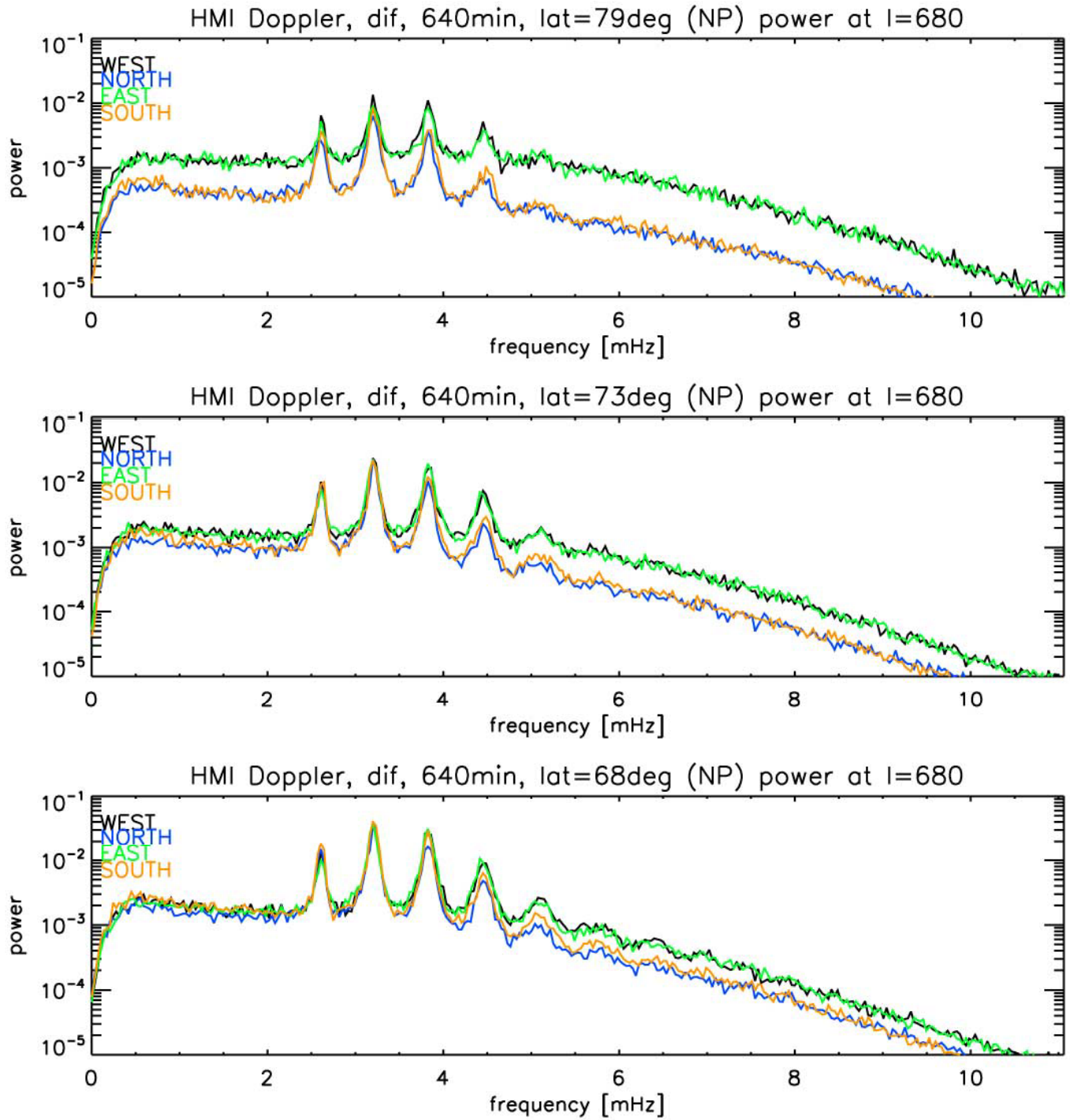
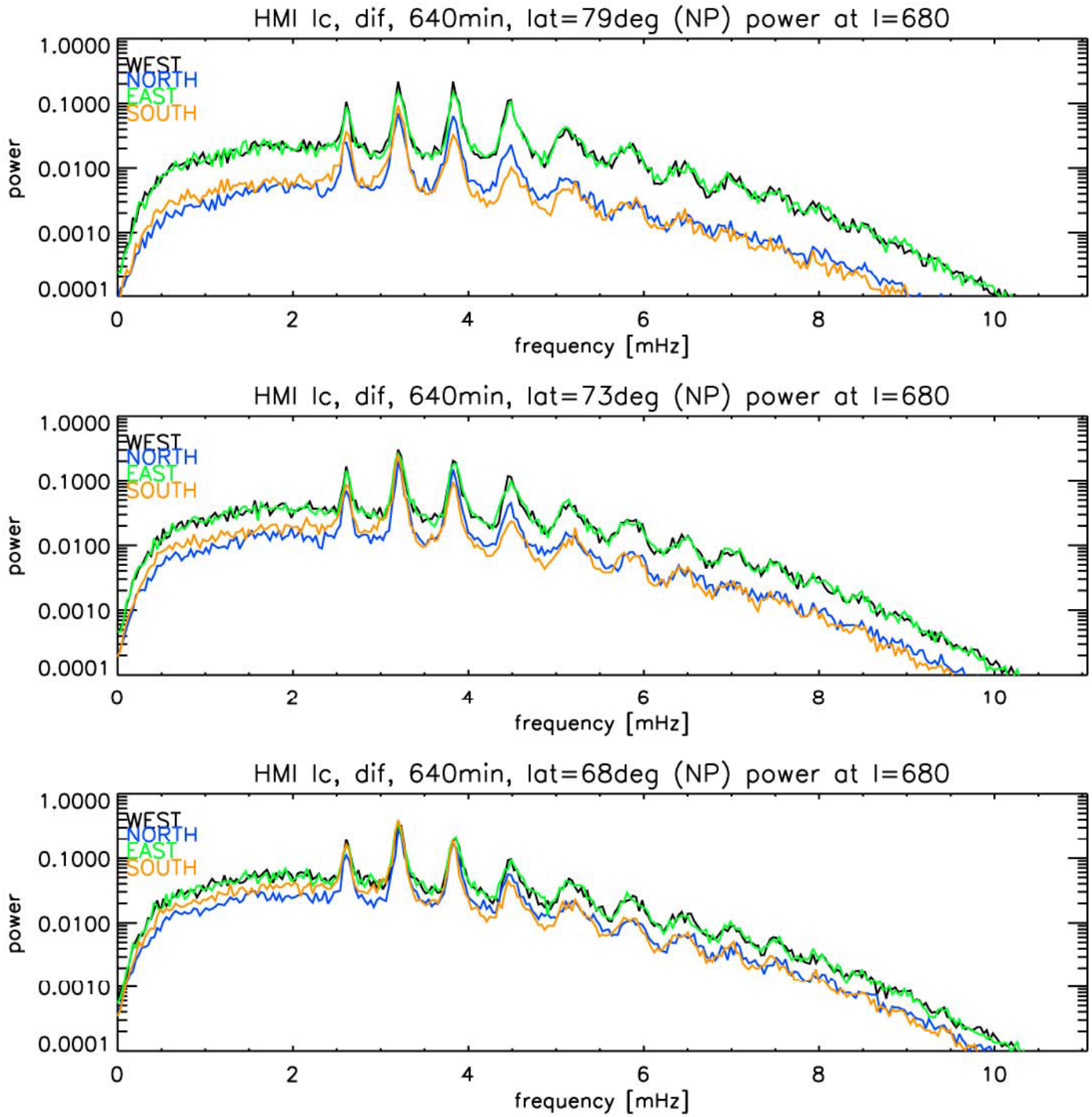
1. Tracked the images
2. Projected the images into the heliographic coordinates by using Postel's projection
3. Calculated power, power spectrum, and cross-correlation functions



HMI Dopplergram power spectrum (at different atitudes in North polar regions)



HMI intensity power spectrum (North polar regions)

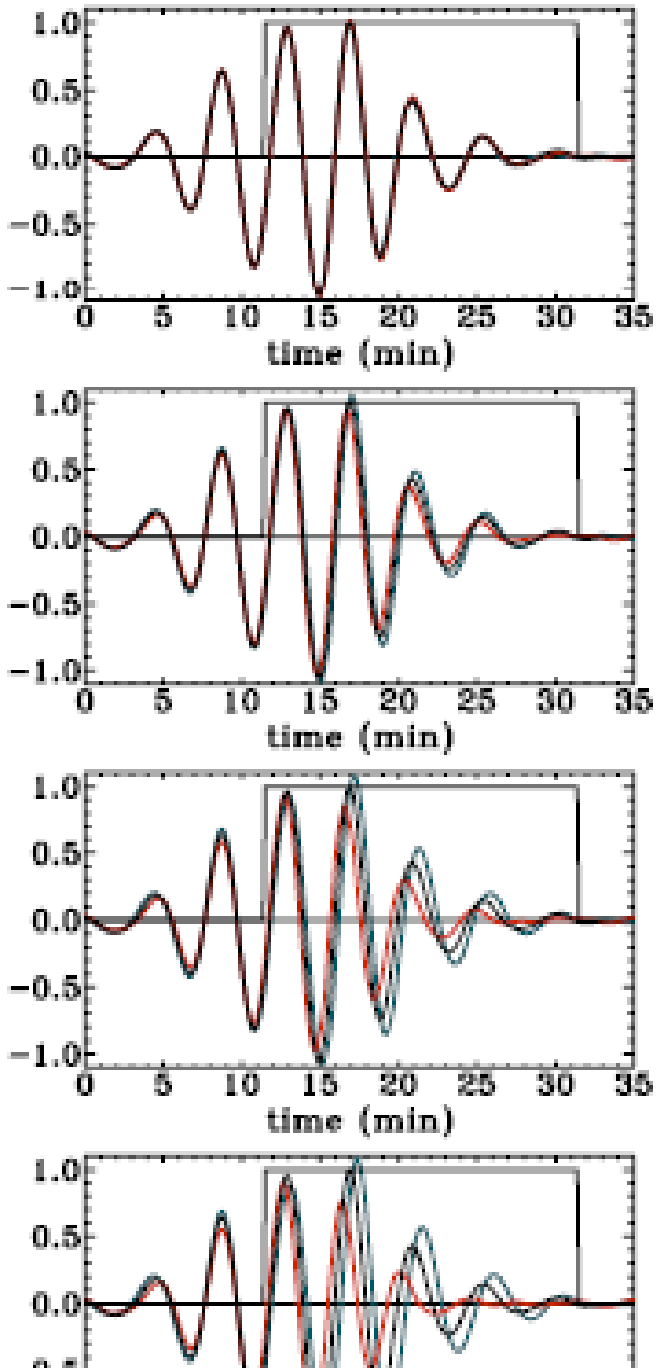
Couvidat & Birch 2009 Figure 1 (part)

without flow

with 200m/s flow

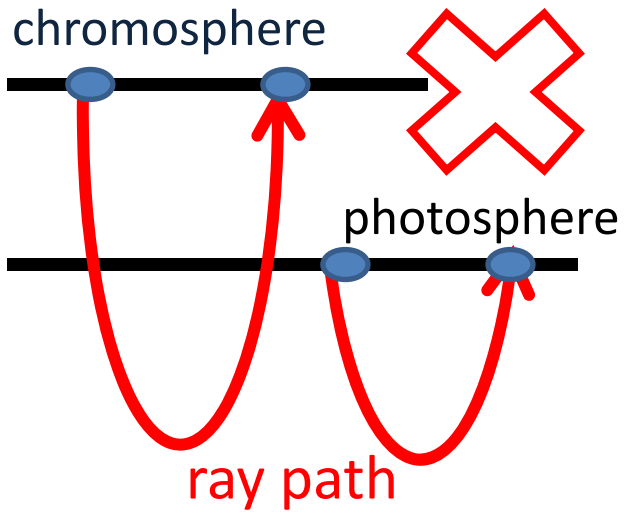
with 400m/s flow

with 600m/s flow



- the shift due to the flow is not parallel

“Travel time” measured above the “surface”

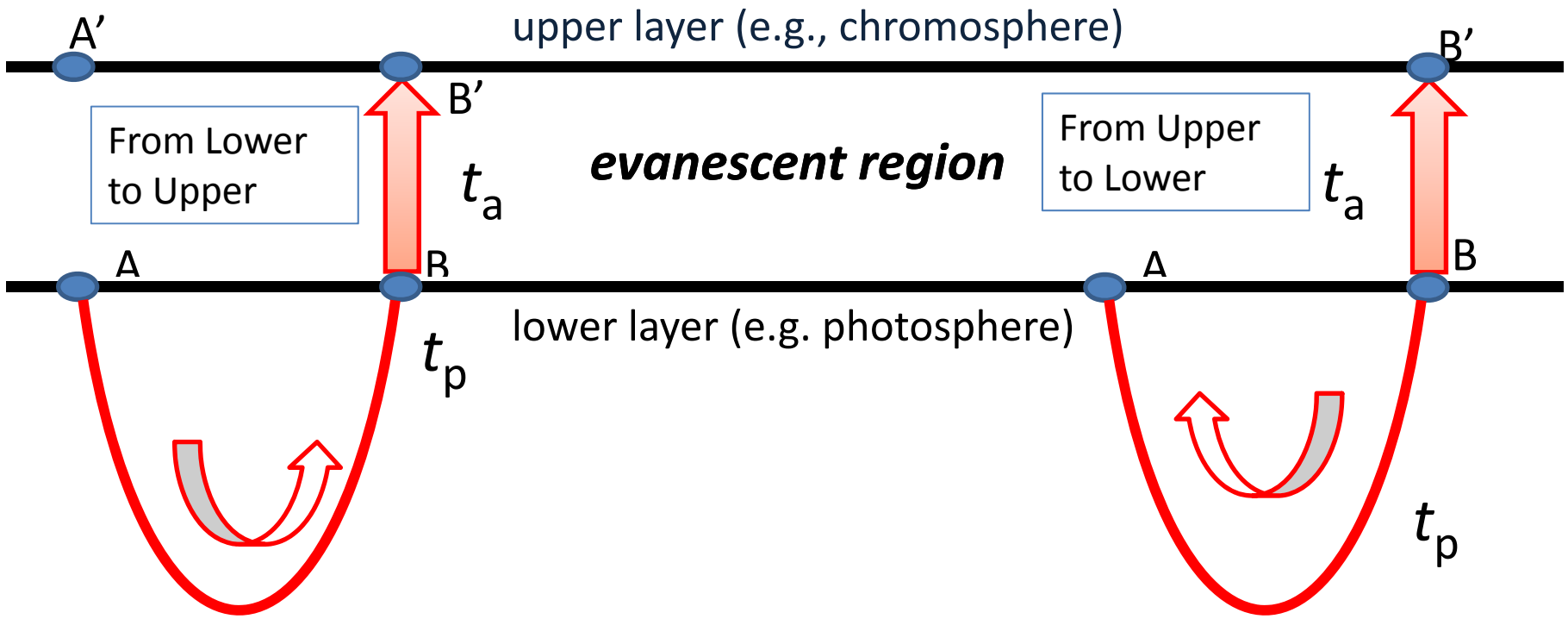


- “Travel time” of acoustic waves is defined as the time interval where the cross-correlation function is strong.

- 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]

(cf. Nagashima et al. 2009 ApJL)

Correct ray path



isotropic case
(no flow, no magnetic field)

from	to	
lower layer	lower layer	$t_{A\text{->}B} = t_p$
upper layer	upper layer	$t_{A'\text{->}B'} = t_p$
lower layer	upper layer	$t_{A\text{->}B'} = t_p + t_a$
upper layer	lower layer	$t_{B'\text{->}A} = t_p - t_a$