How radial is the photospheric magnetic field?

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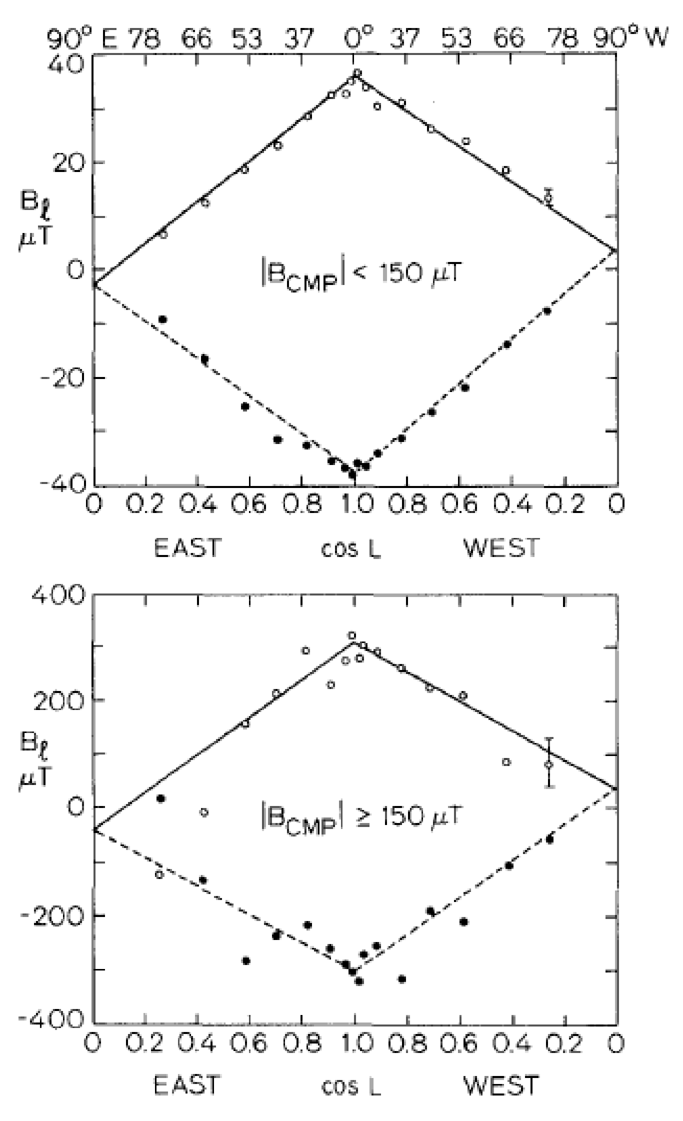
Solar observations

- Line-of-sight observations of the photospheric magnetic field started in late 1950s and calibrated digital data exist since mid 1970s.
- Information about the radial magnetic field Br is important especially for coronal and heliospheric models.
- The simplest and most widely used assumption is that the photospheric magnetic field is radial and B_{LOS} is a projection of the radial field.
- Pseudo-radial magnetic field

$$B_r = B_r^{PSEUD} = \frac{B_{LOS}}{\cos \lambda}$$

Solar observations

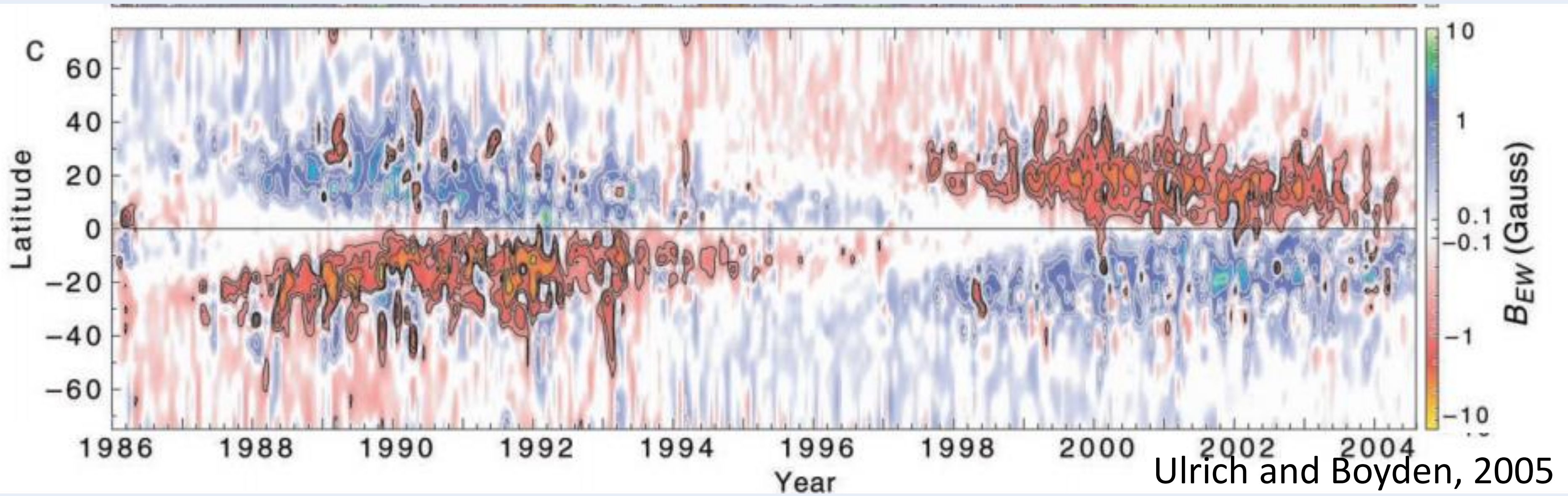
- Originally justified by Svalgaard (1978).
- Observed magnetic field in the same region is proportional to the cosine of the angle from central meridian.
- This method does not pay attention to meridional inclination of the magnetic field.
- Assumption of radial photospheric magnetic field is used practically in all the studies which involve synoptic maps of the photospheric magnetic field.
- How valid it is?



Svalgaard et al., 1978

Toroidal magnetic field

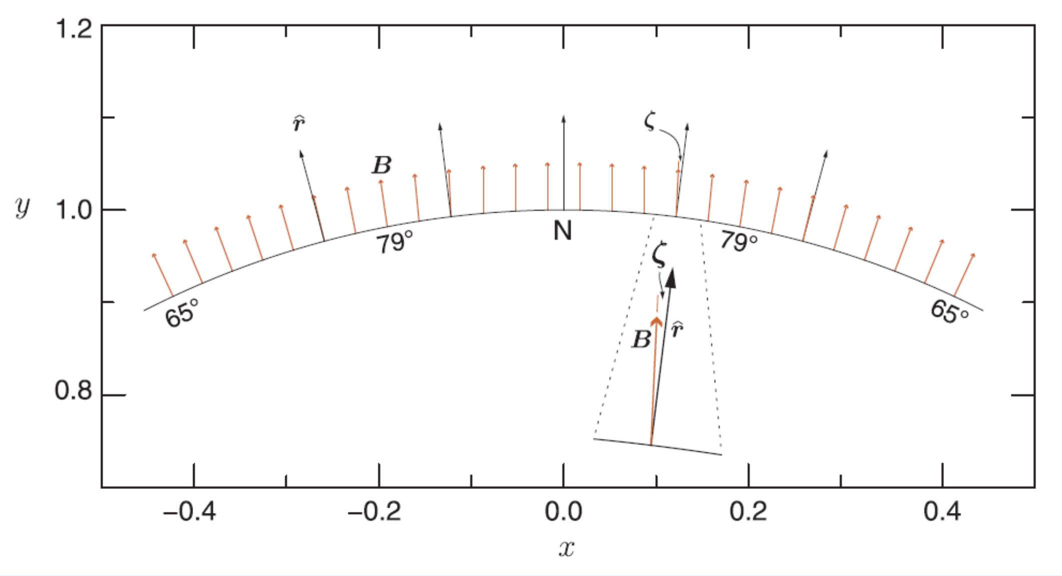
- The average large scale toroidal magnetic field (East-West, B_φ) can be derived using observations on consecutive days, since viewing angle changes about 14 degrees/day.
- A systematic pattern of toroidal magnetic field was found already in 1970s. *(Howard, 1974; Svalgaard et al. 1978 and Duvall et al., 1979).*
- The average B_φ is systematic, but rather small.
- Net tilt in the direction of rotation (to the west) of 0.6° *(Shrauner and Scherrer, 1993)*



Ulrich and Boyden, 2005

Poloidal magnetic field

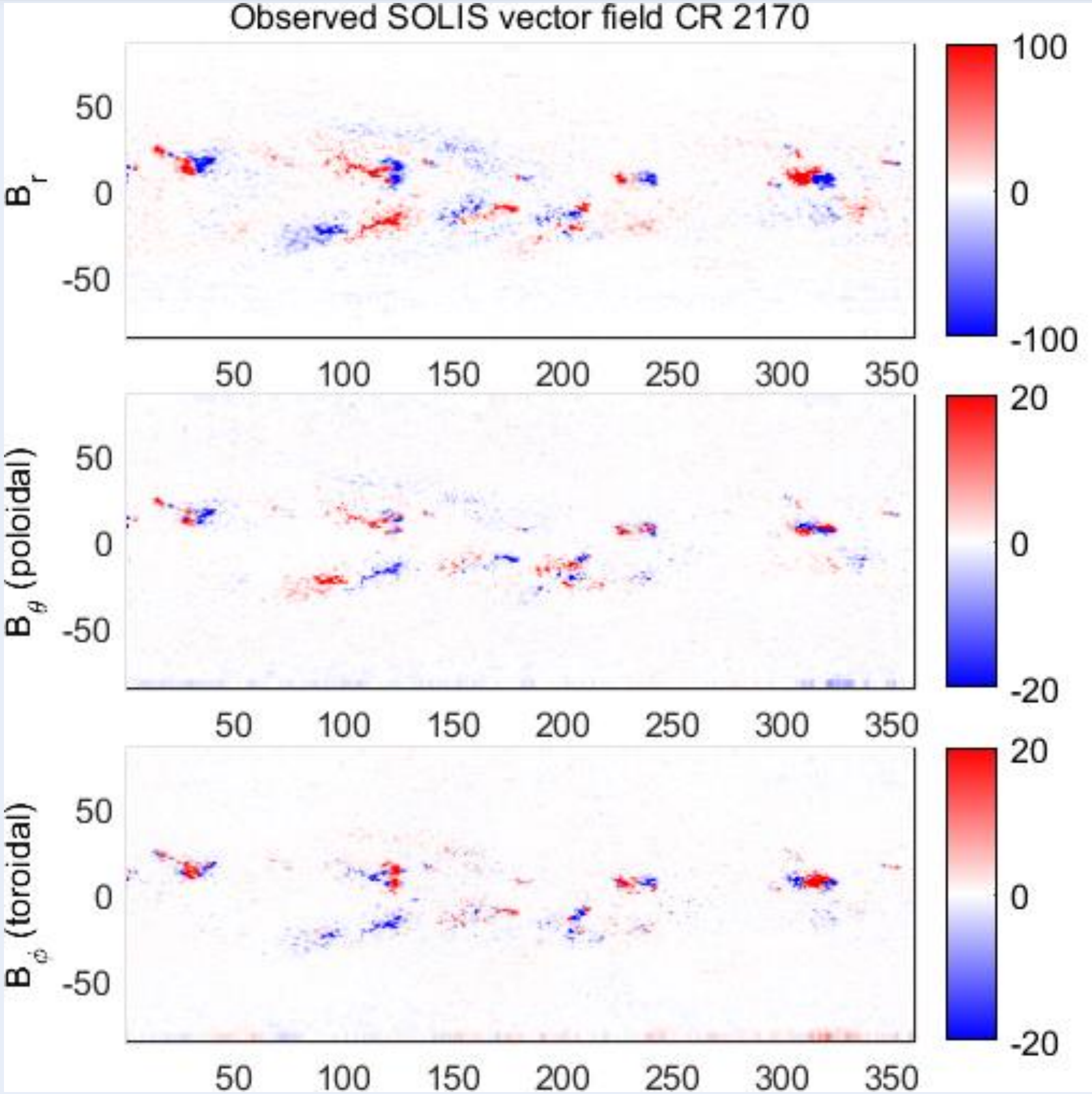
- Poloidal field (North-South, B_θ) is more difficult to derive from B_{LOS} observations since the latitudinal vantage point only varies +-7.25 degrees per year.
- Equatorward inclination of the photosperic magnetic field is often assumed, since coronal magnetic field is known to expand "super-radially" in the ´polar coronal holes.
- Ulrich et al.(2013) suggested that the polar field is few degrees inclined poleward, but the field lines don't converge anyway.
- This assumption and related correction decrease the annual oscillation in observations.



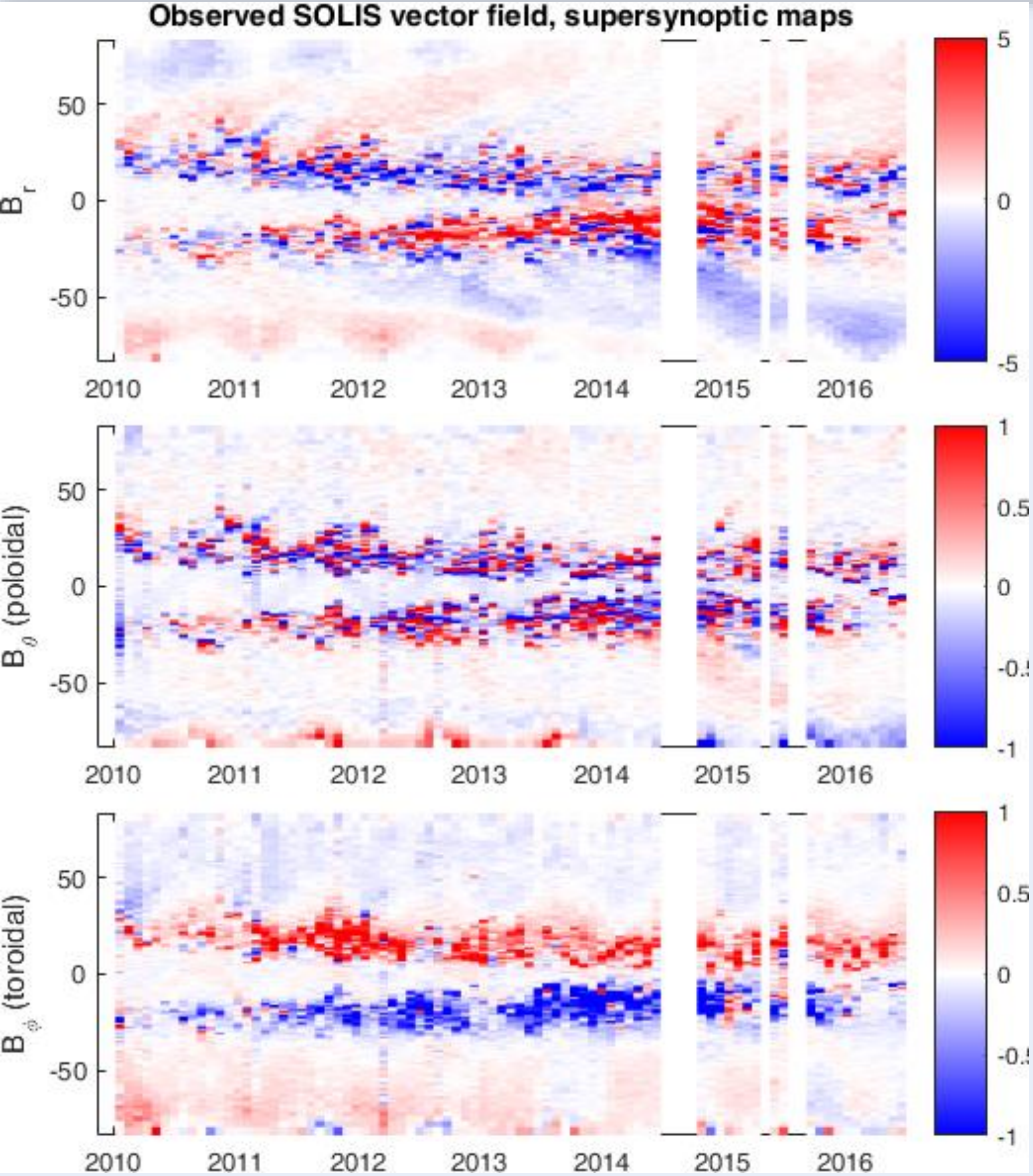
Vector magnetic field

- Synoptic maps of full vector magnetic field should provide us information about the inclination and azimuth of the magnetic field.

- Different data sets:
  - SOLIS, NSO 180*360 pixels
  - HMI, “random calibration” 1440*3600
  - HMI random, 360*720
  - HMI random, 180*360
  - HMI radial, 180*360



Supersynoptic vector map



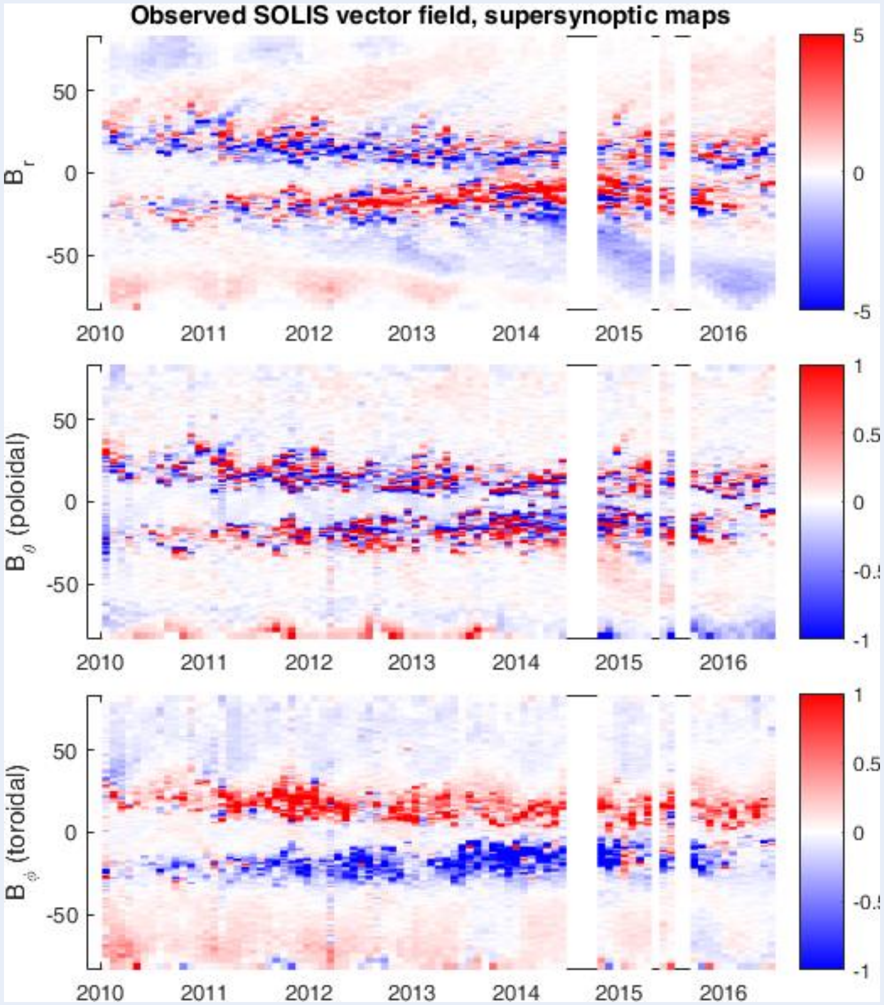
- Longitudinal averages (supersynoptic maps, magnetic butterfly diagram) for three vector components, SOLIS/VSM observations.
- B_r and B_θ have typically same sign in the north but opposite signs in the south.
- This indicates equatorward inclination of the field
- B_φ depicts expected patterns in active regions, following Hale rule but weaker field indicate systematic eastward tilt.

Supersynoptic vector maps

- Very weak B_φ and B_θ in low latitudes, where both components correspond to transverse component in the observations.

- Faint annual "wave" of positive or negative polarity in B_φ and B_θ between active region belts.

- Is the instrument sensitivity too low to observe weak transverse fields?
- The annual variations due to the vantage point effect appear already around 50-60° latitude in vector field.



Inclination and azimuth of the field

- Inclination: Angle between vector and radial direction, varies from 0° to 90°.

$$I = \arctan\left(\frac{\sqrt{B_\theta^2 + B_\phi^2}}{|Br|}\right)$$

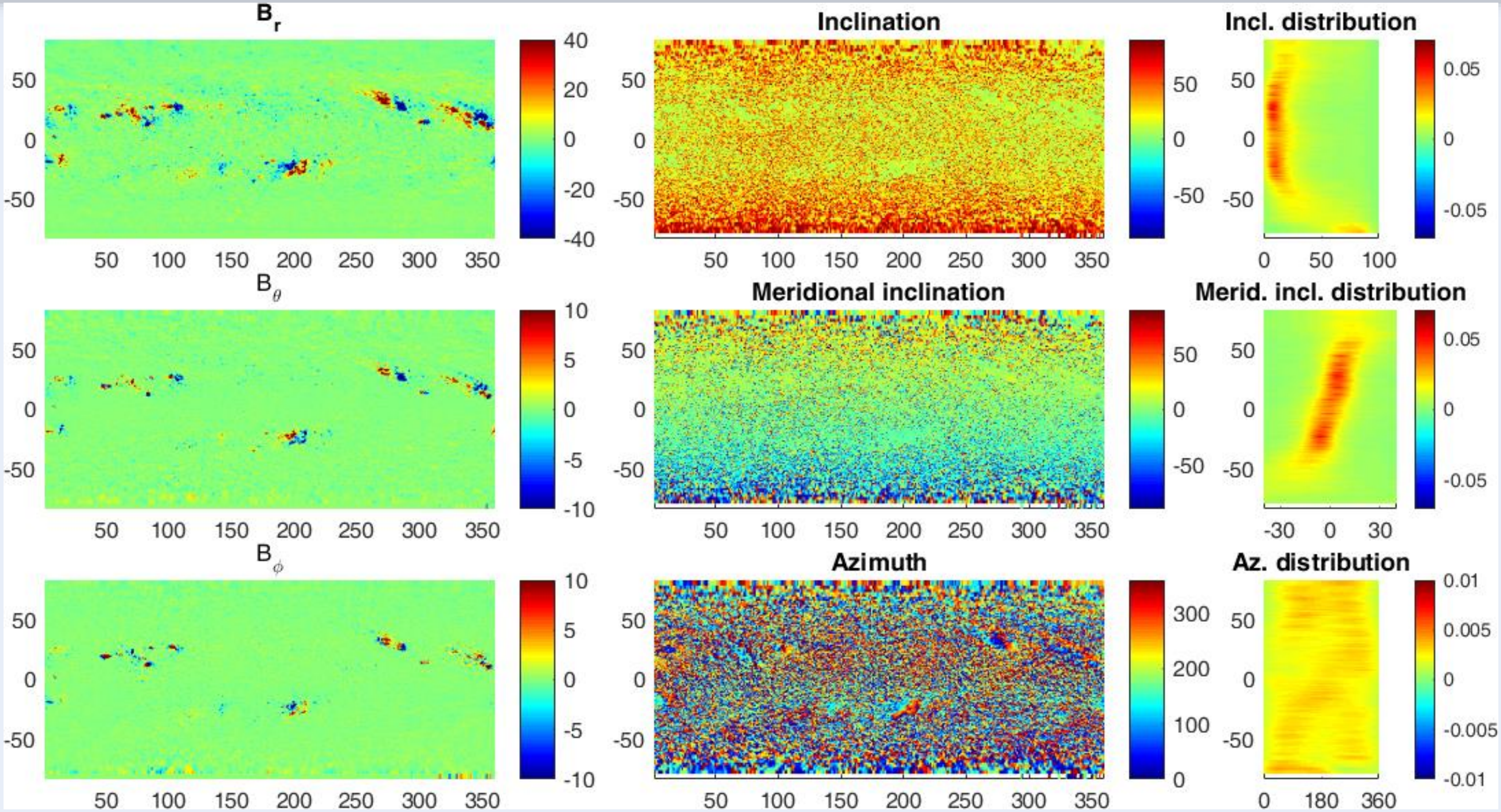
- Meriodional inclination: Angle between $\hat{r}$ and **B**-vector projection to r-θ -plane, varies from -90° to 90°.

$$I_m = \arctan\left(\frac{B_\theta}{Br}\right)$$

- Azimuth: Angle between $\hat{\varphi}$ and **B**-vector projection to φ-θ –plane, zero in the direction of positive B_φ and increases clockwise from 0◦ to 360◦.

$$A = \arctan\left(\frac{B_\theta}{B_\phi}\right) - \left(\frac{B_\phi}{|B_\phi|} - 1\right) * 90°,$$

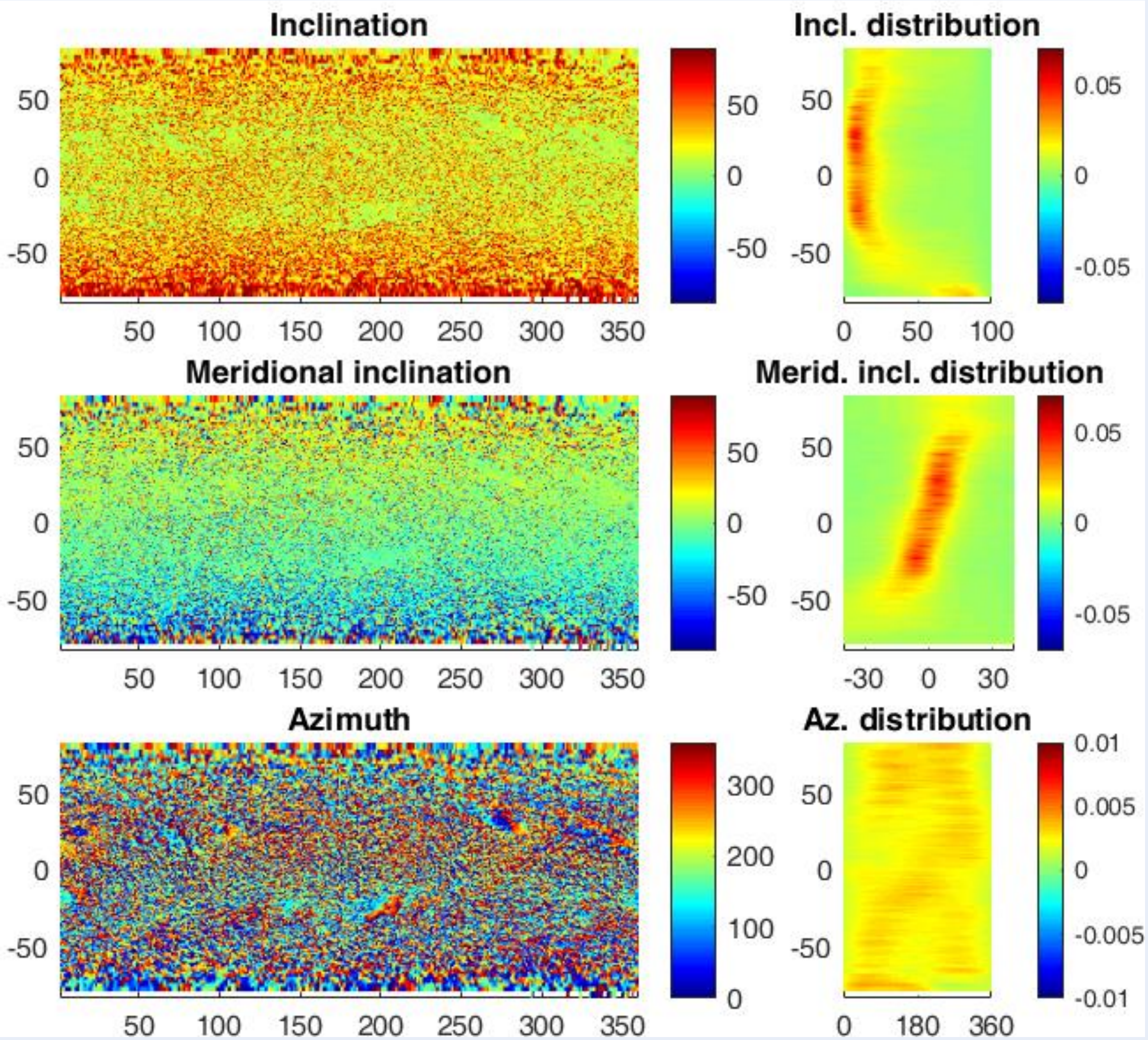
Orientation of the magnetic field



- Left: B_r, B_θ, B_φ , Carrington rotation 2100, SOLIS observations
- Middle: Inclination, meriodional inclination and azimuth.
- Right: Distributions of angles in latitude bins

Orientation of the magnetic field

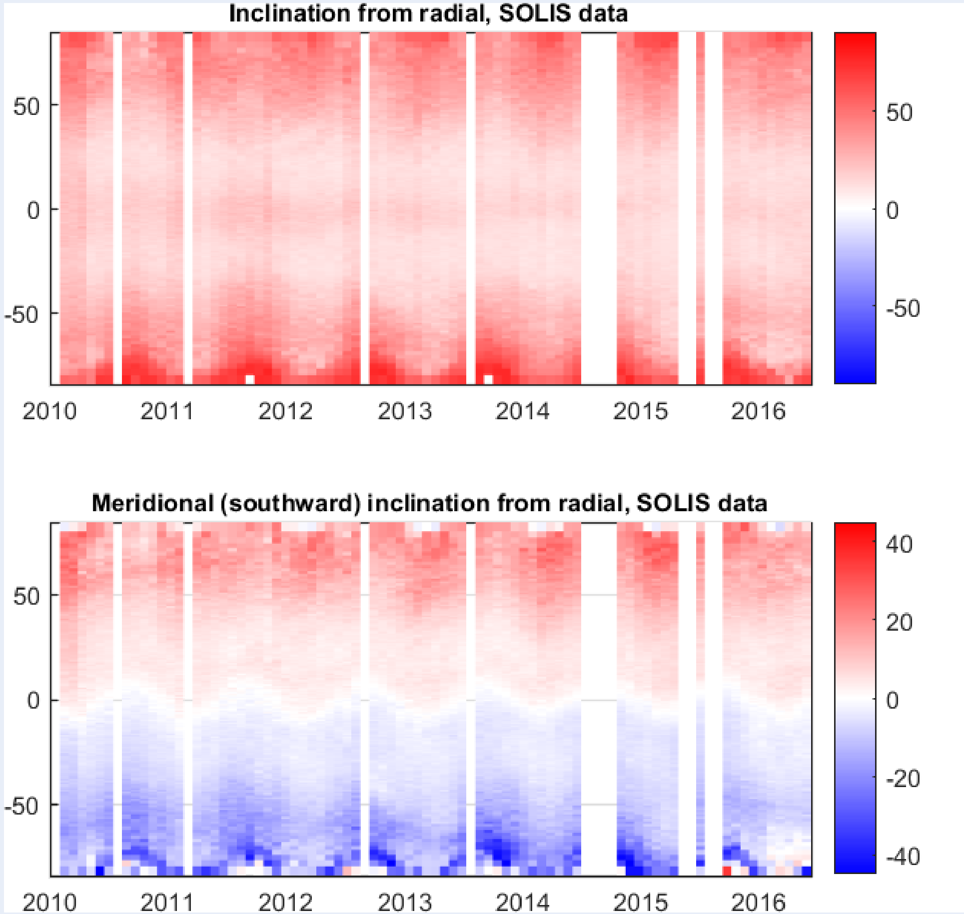
- Field orientation is most radial in active regions.
- Inclination and meridional inclination have obvious latitudinal patterns.
- Field is inclined towards the equator.
- Azimuth distribution is wider and most typical directions are northward and southward.



Supersynoptic median inclination maps

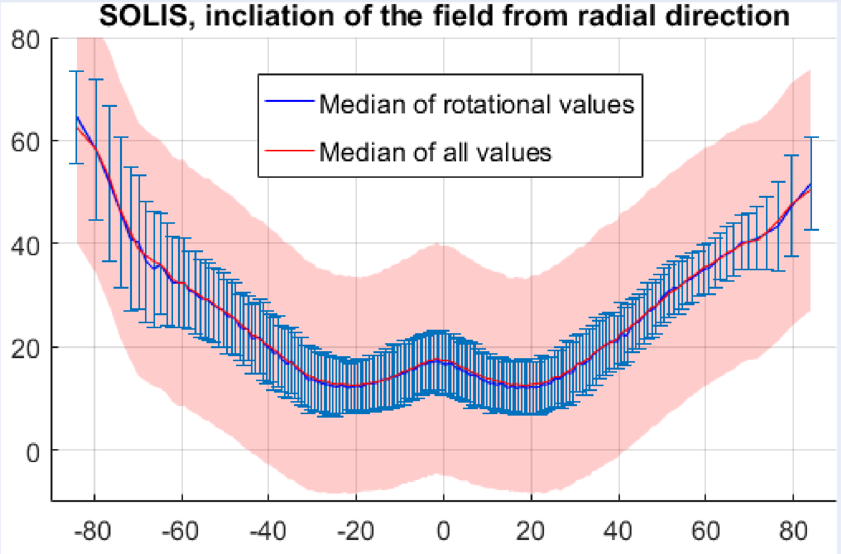
- Longitudinal medians of inclination and meridional inclination.
- Inclination is smallest in mid-latitudes around active regions and increases toward poles and equator.
- Meridional inclination has a systematic pattern of being negative in the south and positive in the north

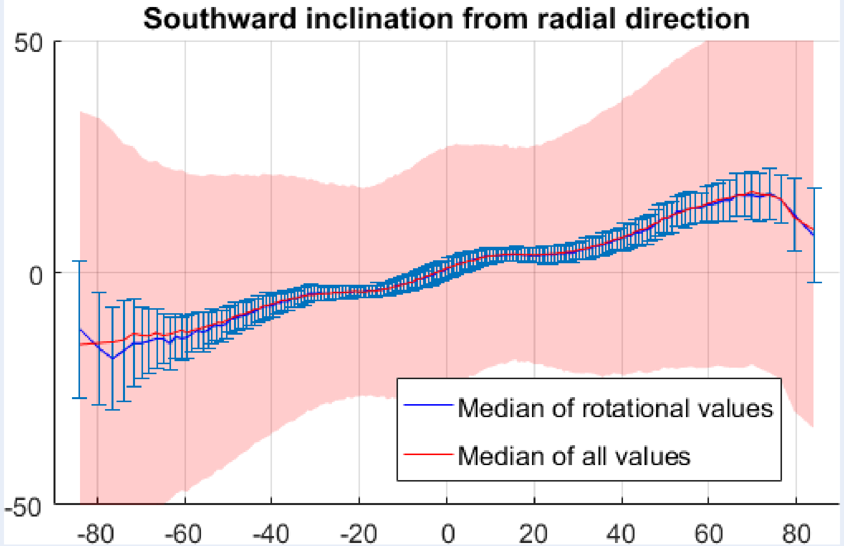
→ Magnetic field is inclined towards the equator in any latitude.



Average inclination

- Average inclination and meridional inclination of the magnetic field based on all SOLIS synoptic vector maps in 2010-2016.
- One sigma error bars.
- Variations are quite large
- Systematic poleward increase of the inclination angle.
- Field is inclined towards equator.





Short SOLIS conclusions

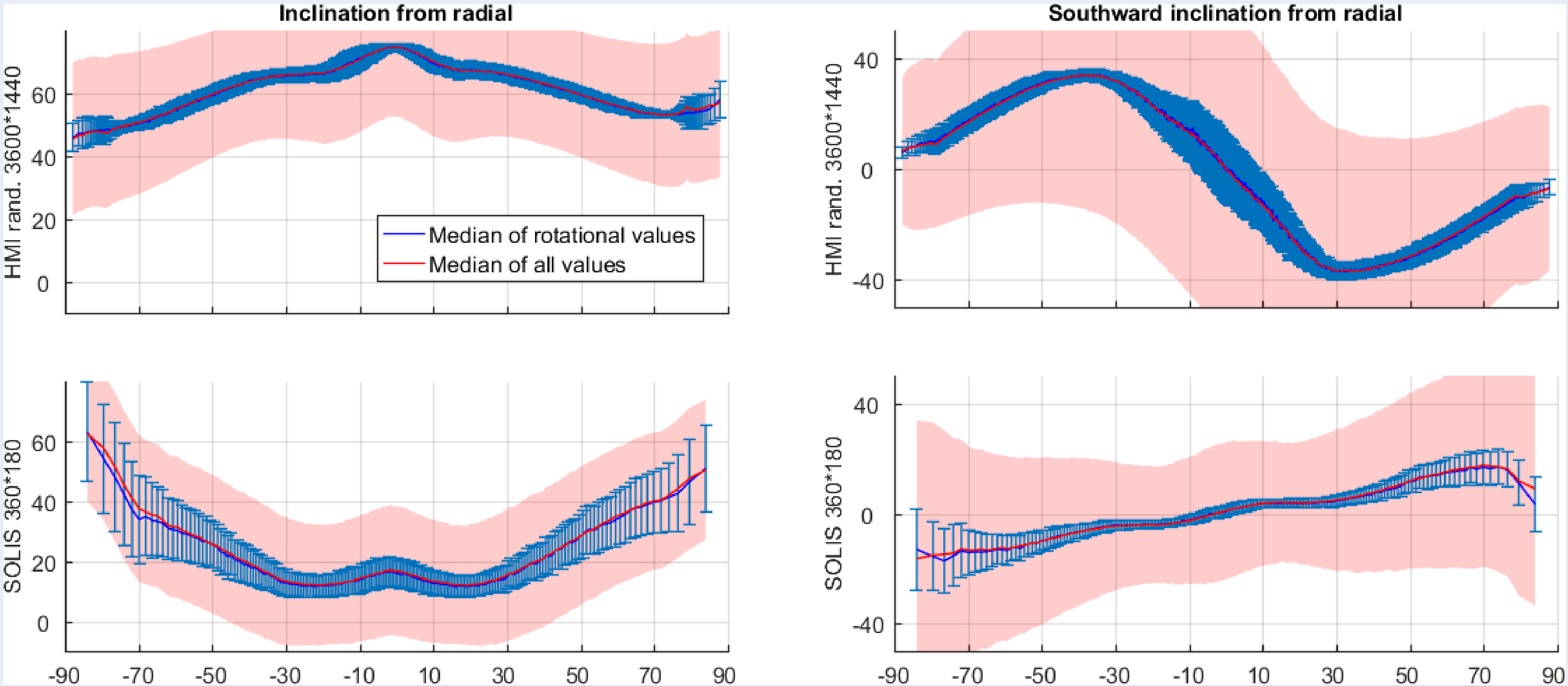
- SOLIS/VSM vector field observations depict that the photospheric magnetic field has a systematic pattern of equatorward inclination.

- This allows to correct derivations of the pseudo-radial magnetic field from line-of-sight observations, radial polar field would decrease significantly.

- However, comparison between SOLIS and HMI lead to unexpected results, two instruments do not agree.

Problems

- SOLIS and HMI results do not agree

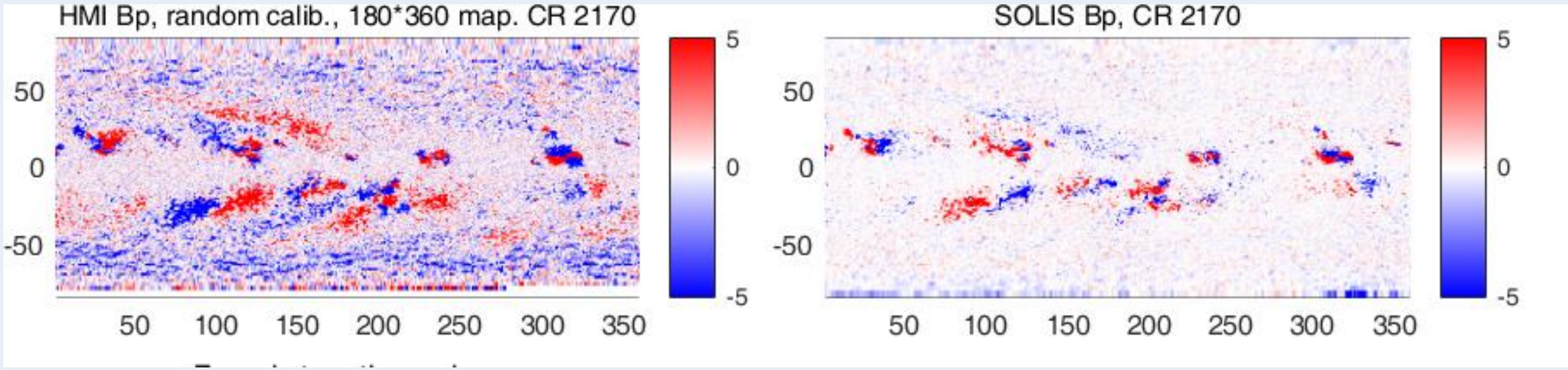


- HMI shows poleward decrease of overall inclination angle.
- HMI also depicts that magnetic field is in general inclined poleward from radial.

HMI vs. SOLIS

- B_r typically agrees, but, B_θ and B_φ only agree in strong fields and have opposite signs in two data sets especially in plages.

- This directly leads to opposite results for inclination.



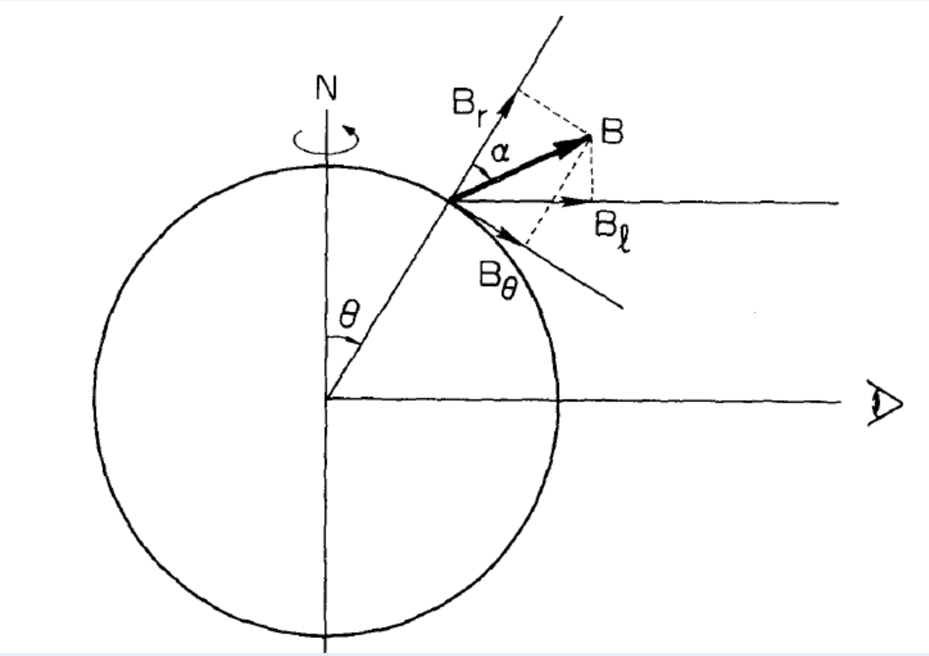
Alternative method to estimate meridional inclination

- Comparison between observed radial vector field Br (“true radial”) and pseudo-radial field derived from line-of-sight observations assuming that field is radial.
- If field is radial:

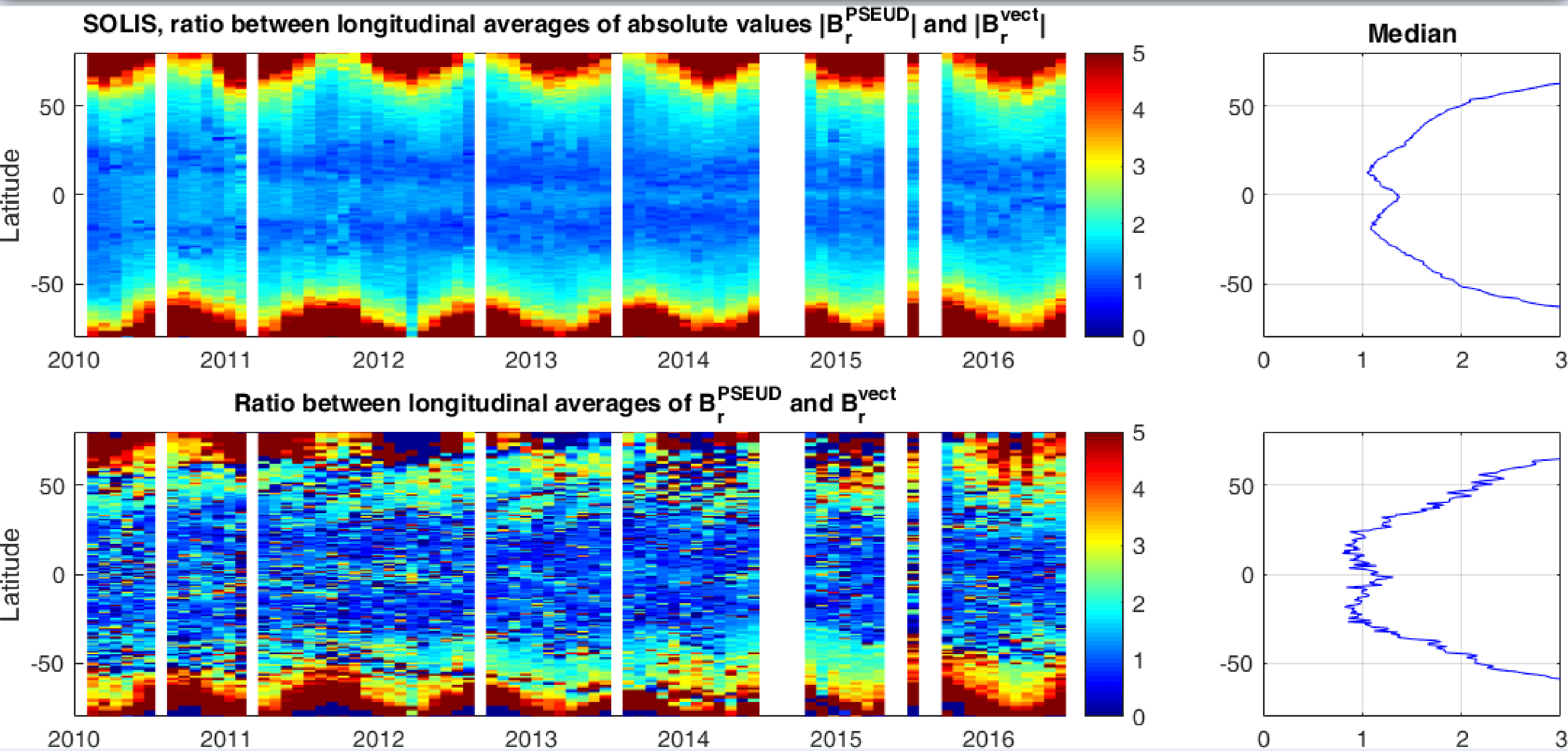
$$B_r = B_r^{PSEUD} = \frac{B_{LOS}}{\cos \lambda}$$

- For equatorward inclination
  $$B_r < B_r^{PSEUD}$$
- For poleward inclination
  $$B_r > B_r^{PSEUD}$$

Assuming that the instrumental effects don’t play role

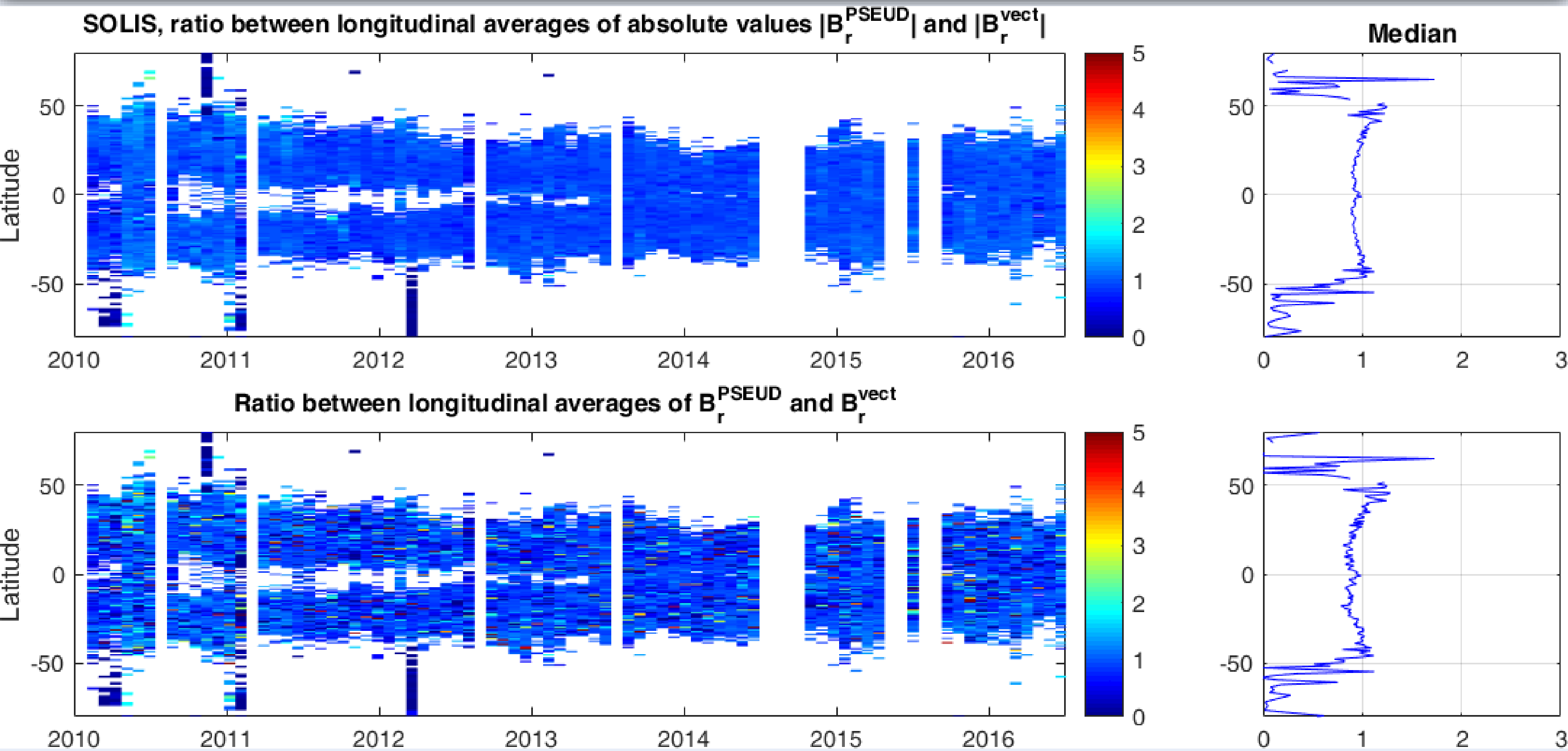


SOLIS true vs. pseudo radial



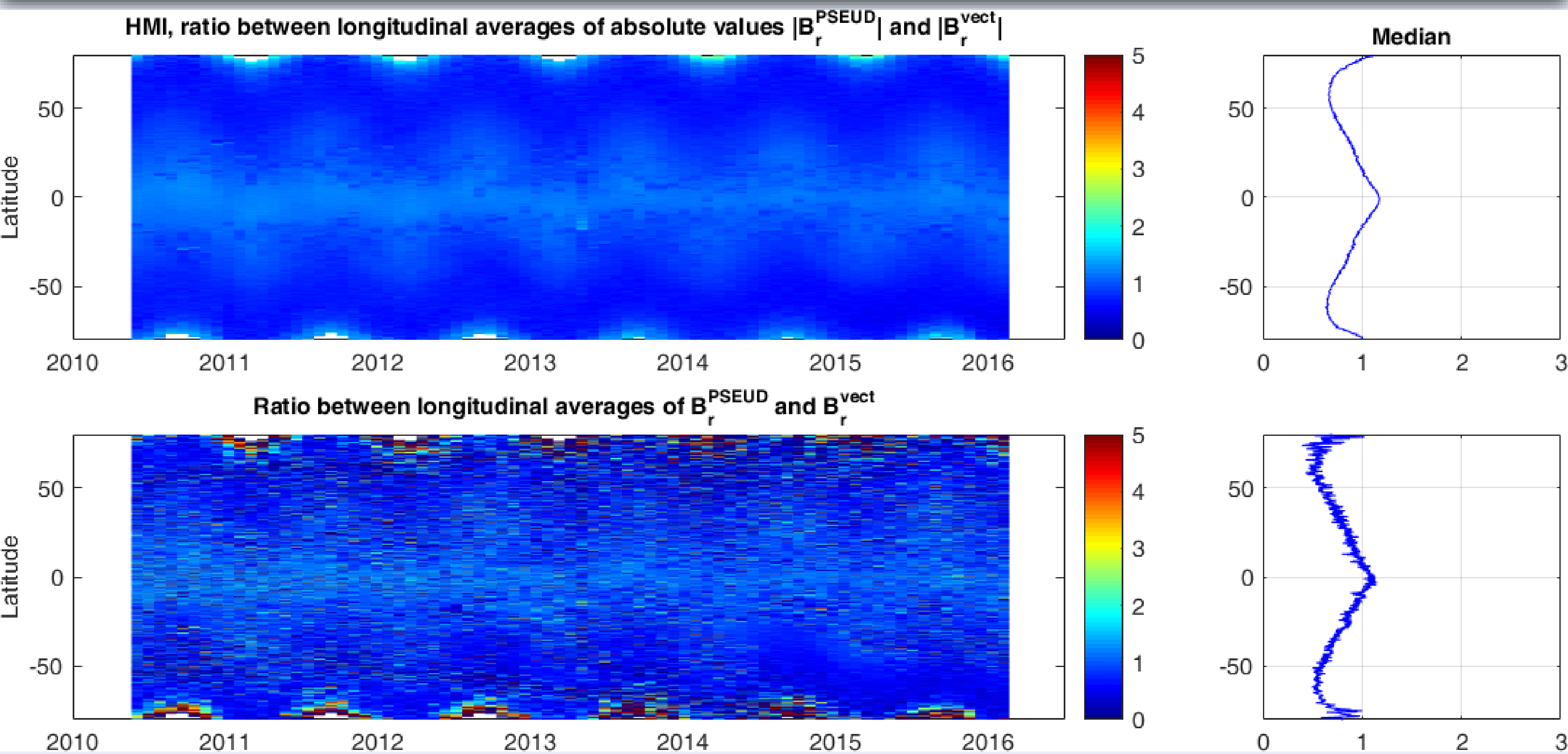
- Vector radial has the same magnitude in active regions, but in the other latitudes pseudo-radial magnitude is larger.
- This would indicate that field inclination is equatorward.

SOLIS true vs. pseudo radial, strong fields



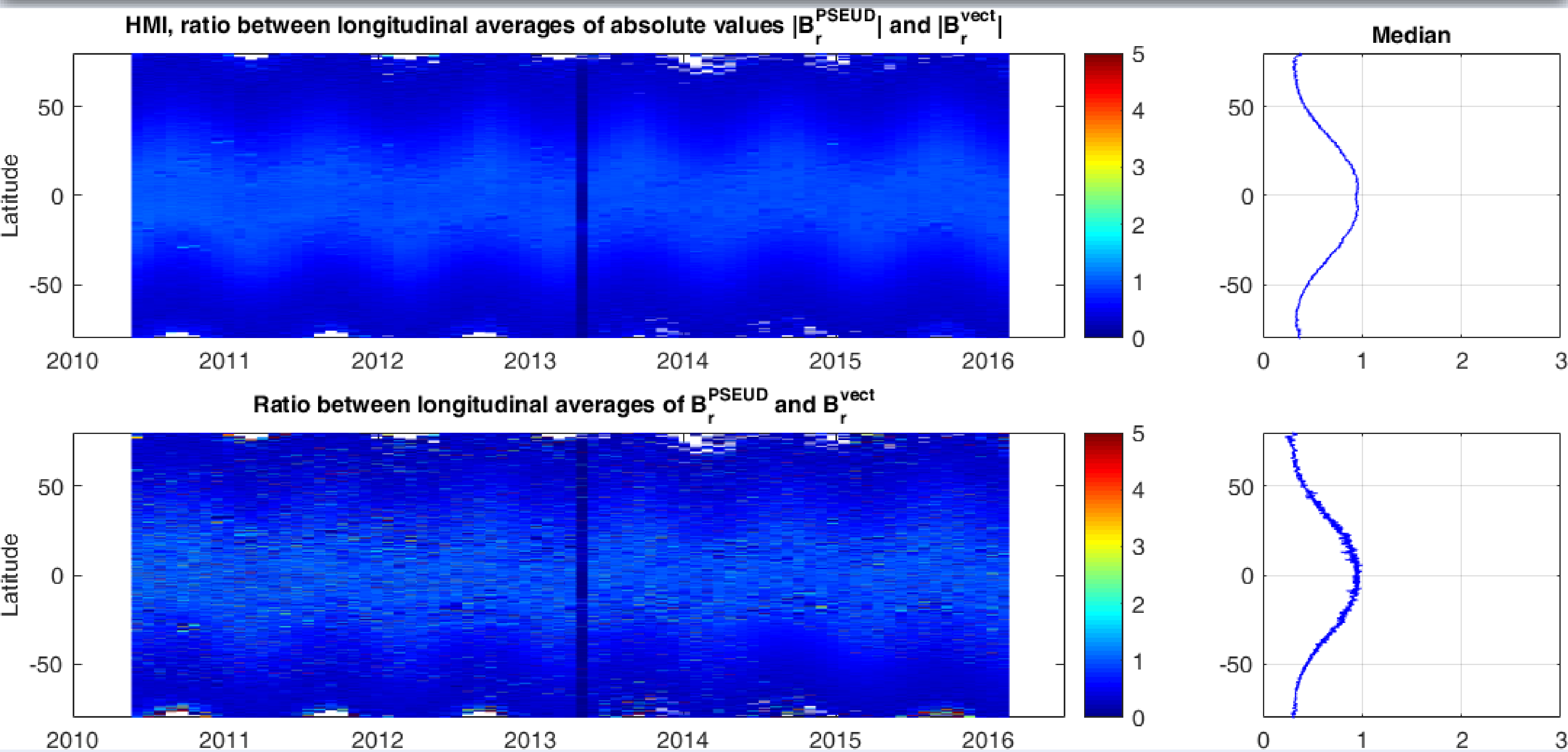
- Same as previous slide, but only pixels where |Br| exceed one sigma threshold are considered.
- Latitudinal profile of the ratio is now way different.

HMI true vs. pseudo radial



- In HMI vector radial and pseudo-radial have the same magnitude around active regions, but in the other latitudes vector radial magnitude is larger.

HMI true vs. pseudo radial, strong fields



- Same as previous slide, but only pixels where Br exceed one sigma threshold are considered.
- Different profile also for HMI when considering only strong fields.

Final conclusions

- SOLIS/VSM and HMI vector field observations indicate that photospheric magnetic field is systematically tilted from radial.
- SOLIS depicts that tilt is towards equator and HMI that tilt is towards poles.
- Comparison between vector radial and pseudo-radial fields don't solve this conflict, both data sets are self consistent.
- Ratio between vector radial and pseudo radial is non-linear.
- HMI results also depend on resolution and disambiguation method.
- High latitude observations are less noisy and field strength is larger in HMI.
- Obvious contradiction between two data sets, no final conclusions yet.