Estimation of projection effects in the solar polar magnetic flux measurements from an ecliptic point of view

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Motivation:
- The determination of the distribution and evolution of the polar magnetic flux is important for solar cycle and dynamo studies.

Polar observations are challenging from the ecliptic view:
- Quiet-Sun magnetic flux is mostly vertical:
  →Oblique view means weak Stokes-V signals.
- Foreshortening causes coarser spatial sampling per pixel:
  →Net flux averaged over polar regions is underestimated due to sub-pixel flux cancellation.

Interpretation is challenging:
- Spectral lines form over a range of heights in the solar atmosphere.
- B decreases with height as flux elements expand upwards to maintain lateral pressure balance.
- Inclined line-of-sight (LOS) samples different depth in the solar atmosphere compared to vertical LOS.

Current Study:
- Considers projection effects only on LOS measurements.
- Systematic errors only: No instrumental noise considered.
- Uses realistic MHD simulations of quiet sun magnetic network as input to synthesize Stokes profiles of the Ni I 676 nm line.
- Stokes profiles are synthesized with various ray projections through the model atmosphere.
- Apply center-of-gravity (COG) algorithm to the Stokes I±V profiles to infer "synthetic" LOS magnetic field (B_{LOS}) maps.
- Use the B_{LOS} maps to study net flux variation with LOS.
- Actual B_z at τ_{500}=1 surface in the MHD cube is taken as the ground truth.

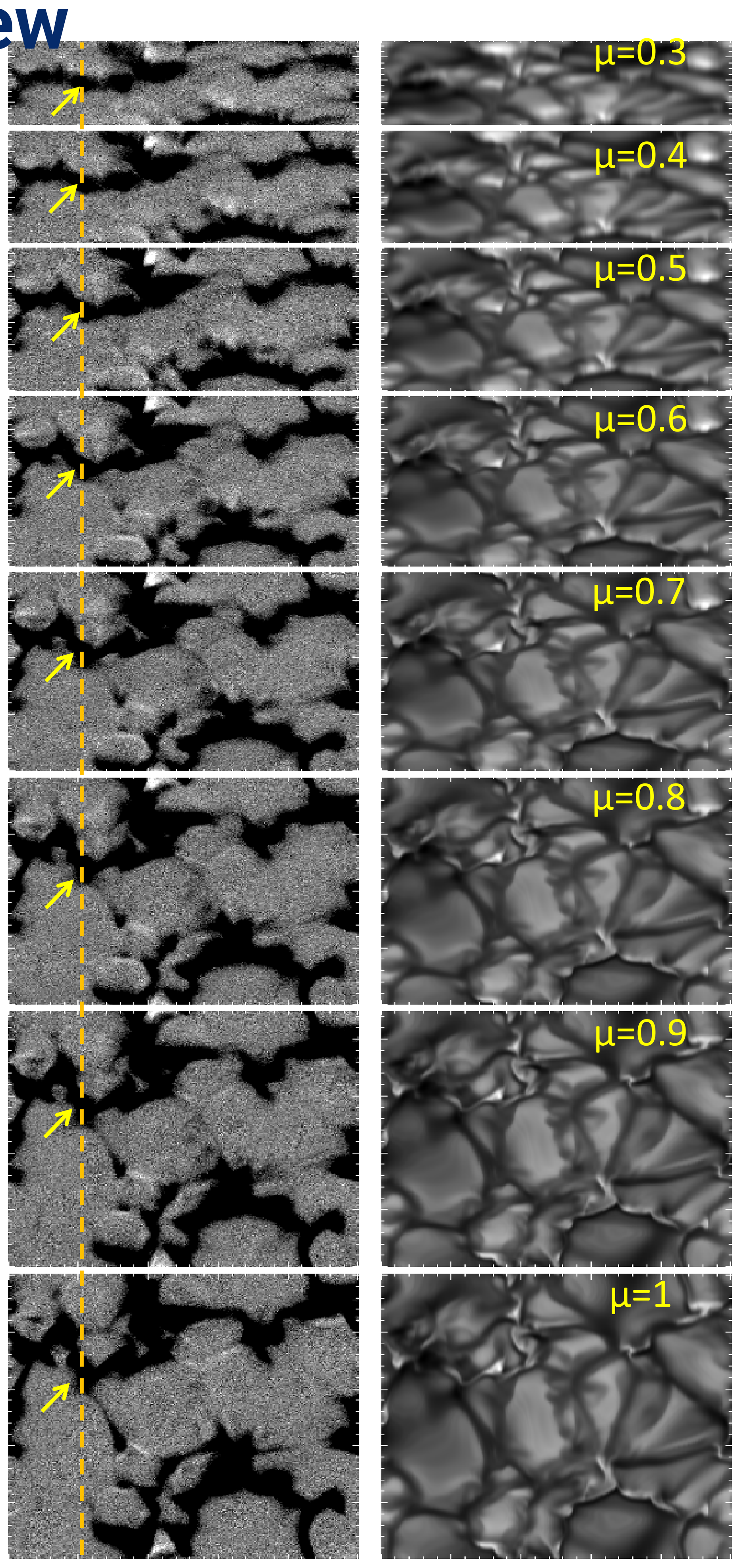


Fig 1. A mosaic of synthetic LOS magnetograms (left column) and the continuum intensity map (right column) computed for different viewing angles (μ=cos θ) from a numerical MHD and radiative transfer model of the quiet Sun network is shown. Geometric foreshortening along y-direction and "bread loaf" like appearance of granules can be noticed. The yellow arrow shows the network lane feature which is sampled along vertical dashed yellow line for further study.

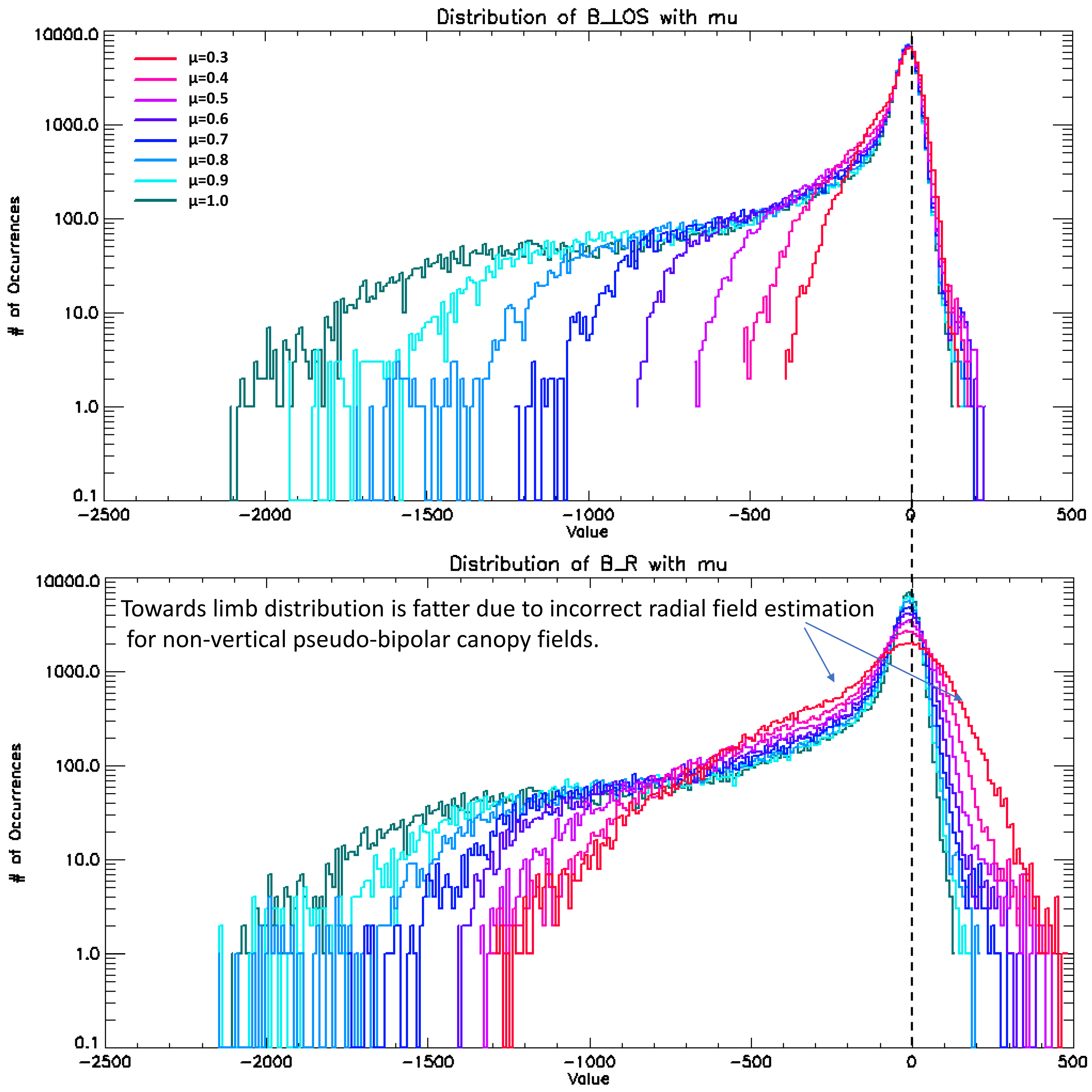


Fig 2. The histograms of the B_{LOS} as inferred from various viewing angles (μ=cos θ) is shown in top panel where μ is color coded. The number of pixels measuring stronger flux reduces systematically as is expected for the case of predominantly vertical flux tubes in intergranular network region. Traditionally, the radial flux B_R(=B_{LOS}/ μ) is computed from B_{LOS} under the assumption that flux is predominantly vertical outside of the active regions. The histograms of the B_R flux inferred under this assumption at various μ are shown in the bottom panel.

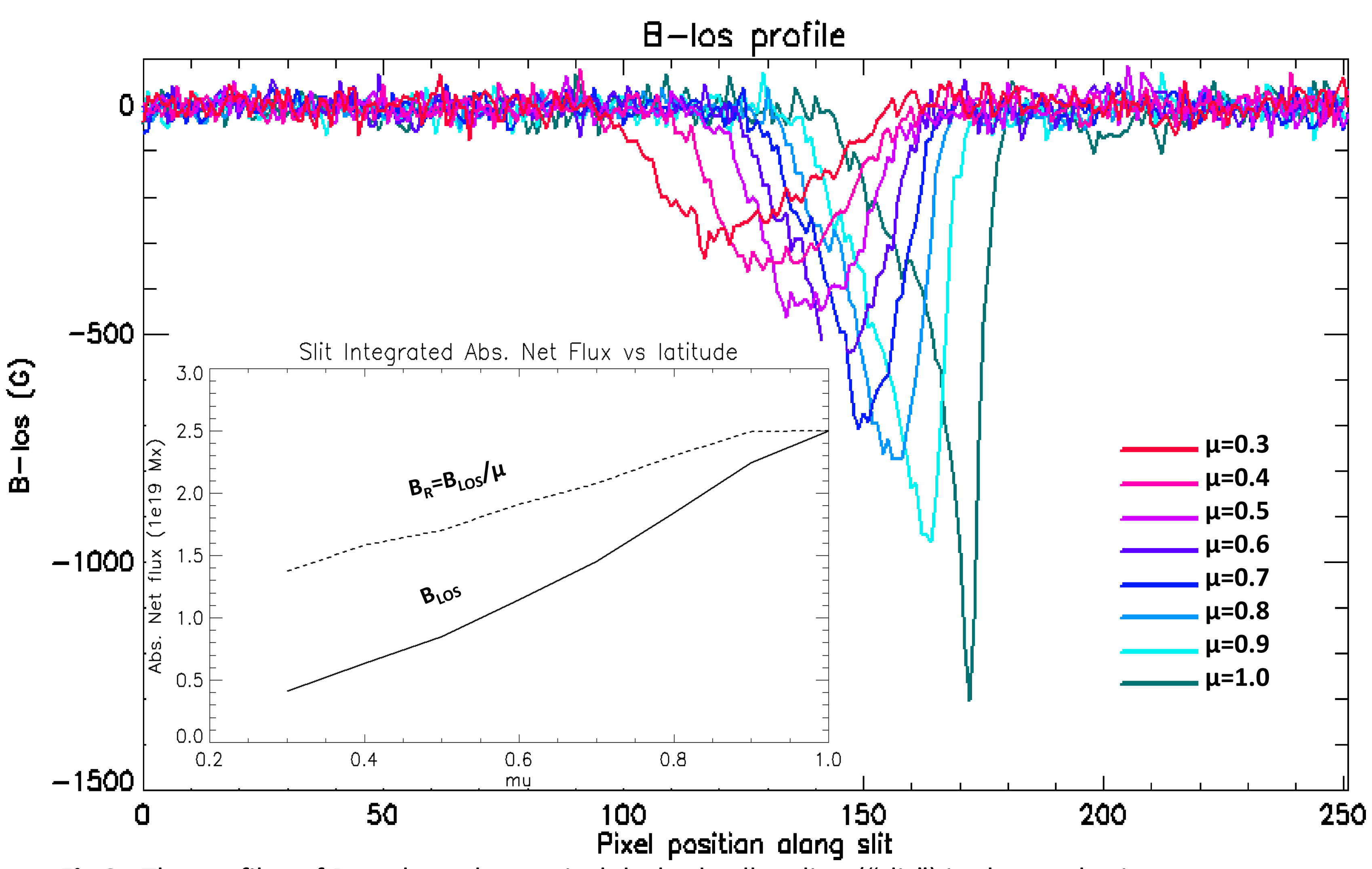
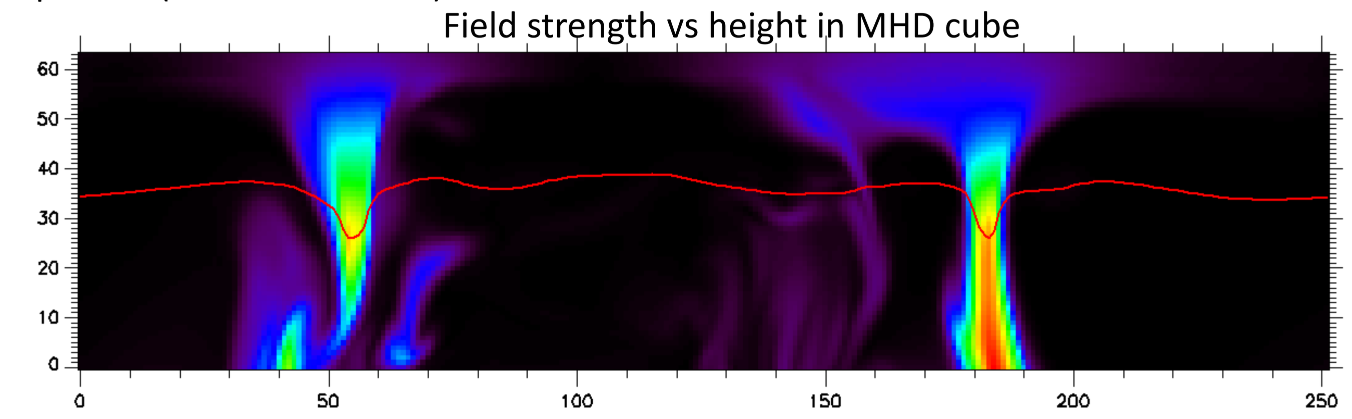


Fig 3. The profiles of B_{LOS} along the vertical dashed yellow line ("slit") in the synthetic magnetograms shown in the mosaic of figure 1 is shown here with the profile colors coded according to the μ value. The inset shows the variation of the absolute value of net flux (**B_{LOS}**), integrated over the area covered by the slit, as function of mu. Also shown is the variation of the estimated radial flux, **B_R=B_{LOS}/μ**, with μ ~~value~~ (the dotted curve).



Results:
The mean magnetic flux in solar polar regions inferred from LOS magnetographs is underestimated because of several reasons:
(a) The magnetic field is predominantly vertical in quiet Sun network regions→ diminishing Stokes-V signal→ missing weaker flux below the noise limit of the measurements.
(b) Under the assumption that field is predominantly vertical, the radial flux is estimated as B_R=B_{LOS}/ μ . This has the following implications:
- Flux tubes are vertical only in the darkest intergranular lanes, flux tubes expand outside this region to form a magnetic canopy.
- The canopy fields have a pseudo-bipolar appearance away from disk center, just like unipolar round sunspots appear pseudo-bipolar when viewed away from the center of the disk.
- Due to foreshortening, a part of this pseudo-bipolar canopy flux would cancel due to sub-pixel cancellation.
- Even if the canopy flux is spatially resolved, applying a vertical flux assumption to pseudo-bipolar canopy flux causes artificial broadening of histogram FWHM (lower panel of Fig 2.)
- Performing spatial average (over polar regions) of the pseudo-bipolar canopy flux leads to flux cancellation and hence an underestimation of the polar flux.
- The changing B-angle of the Sun during ecliptic observations further complicates these measurements.

(c) The optical depth unity (τ=1) surface samples deeper parts of the flux tube atmosphere, when viewed near disk center, as compared to inclined LOS, which effectively samples progressively higher layers with viewing angle.

Conclusions:
With the oblique view of polar region the magnetic flux is underestimated by the LOS magnetograms due to two compounding effects:
(i) LOS samples progressively higher layers of the flux tube atmosphere where the magnetic configuration is no longer dominantly vertical but has more of a canopy-like configuration.
(ii) The deep-rooted stronger vertical flux remains obscured/poorly viewed from the inclined LOS. Unfortunately, the approximation B_R=B_{LOS}/ μ is only valid for this vertical part of the flux tube.
(iii) The inclined view samples the canopy region of flux tubes giving a pseudo-bipolar appearance, which does not contribute to net flux estimates when simply spatially averaged and/or due to foreshortening caused sub-pixel cancellation.
(iv) In principle, vector field measurements should help, however, they suffer from issues such as magnetic fill factor, 180-degree azimuth ambiguity and differential QU versus V noise issues.