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Underestimation of the polar magnetic flux measurements due to projection effects from the ecliptic view

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Motivation:

The distribution and evolution of the polar magnetic flux is important for solar cycle, dynamo studies and to address "solar open flux problem".

Polar observations are challenging from the ecliptic view:

- Dominant quiet sun magnetic flux is mostly vertical:
  →Oblique view means poor Stokes-V signals.
- Foreshortening causes coarser spatial sampling per pixel:
  →Observed flux is underestimated due to sub-pixel flux cancellation.

Interpretation is challenging:

- Spectral lines form over a range of heights in solar atmosphere.
- B reduces with height as flux tube expands to maintain lateral pressure balance.
- Inclined line-of-sight (LOS) samples different depth (upper layers) in solar atmosphere as 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 676.8 nm absorption line, of GONG and MDI heritage.
- Stokes profiles are synthesized with various ray projections (μ=0.3-1.0) 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 viewing angle.
- Actual B_z at τ_{500}=1 surface in the MHD cube is taken as the ground truth.

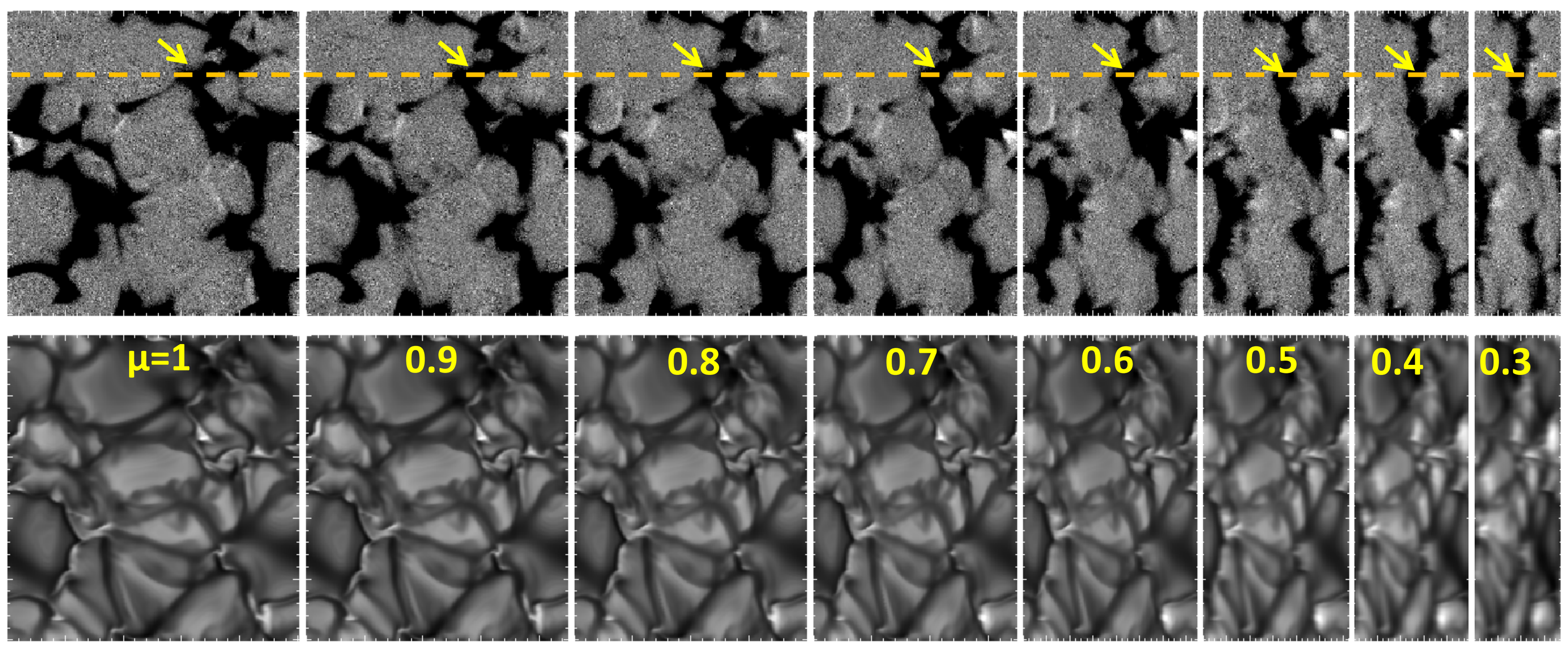
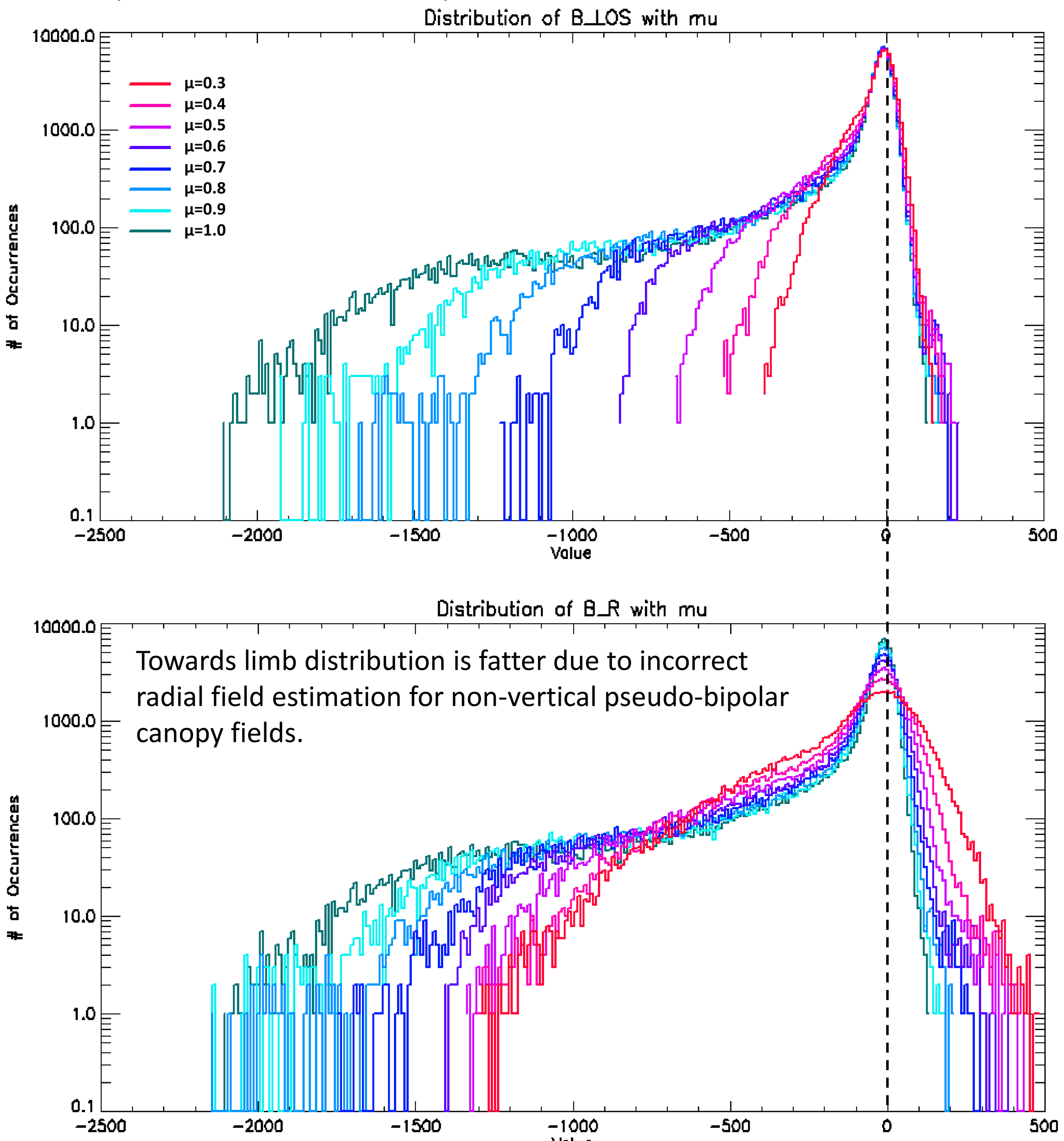


Fig 1. A mosaic of synthetic LOS magnetograms (left column) and the continuum intensity map (right column) computed for different viewing angles (μ=cos θ) from a numerical MHD and radiative transfer model of the quiet Sun network is shown. Geometric foreshortening along y-direction and "bread loaf" like 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.



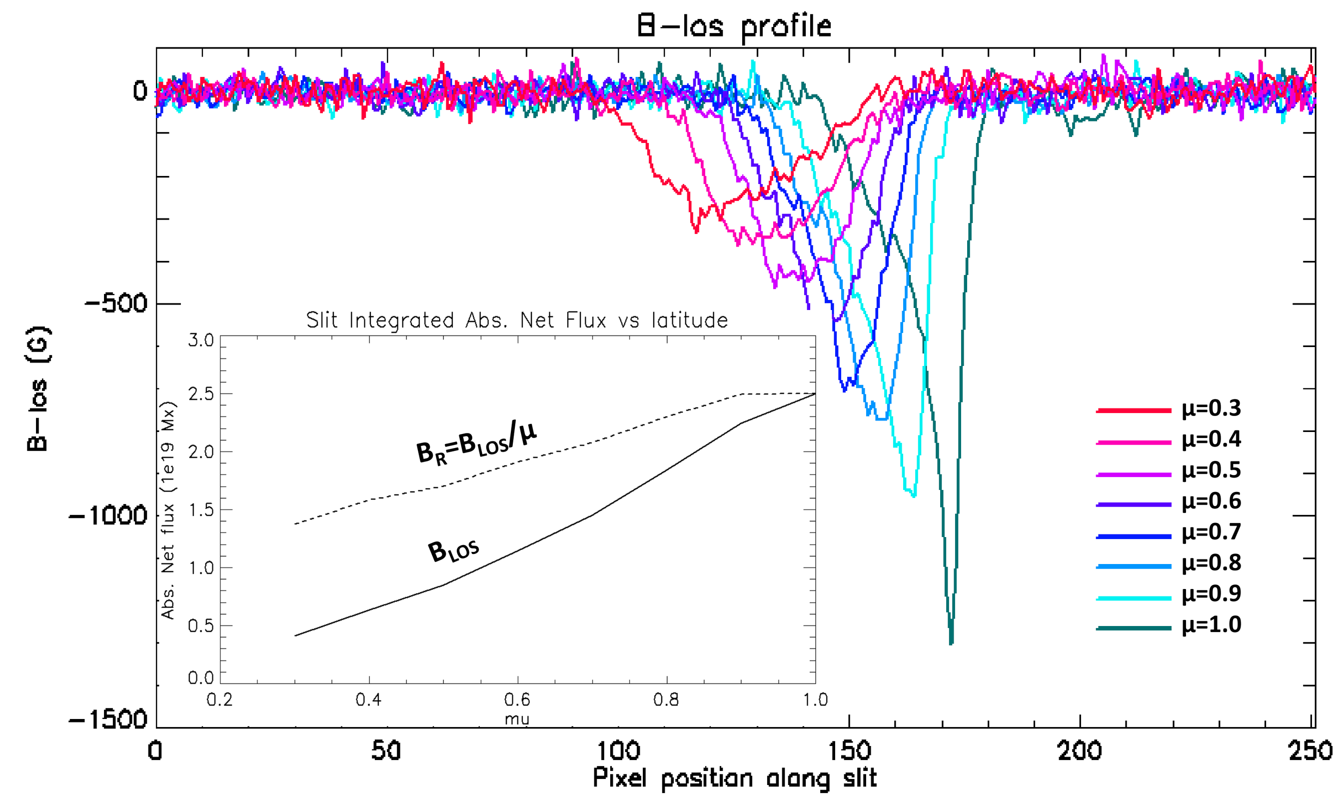


Fig 3. The profiles of B_{LOS} along the vertical dashed yellow line ("slit") in the synthetic magnetograms shown in the mosaic of figure 1 is shown here with the profile colors coded according to the μ value. The inset shows the variation of the absolute value of net flux (**B_{LOS}**), integrated over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

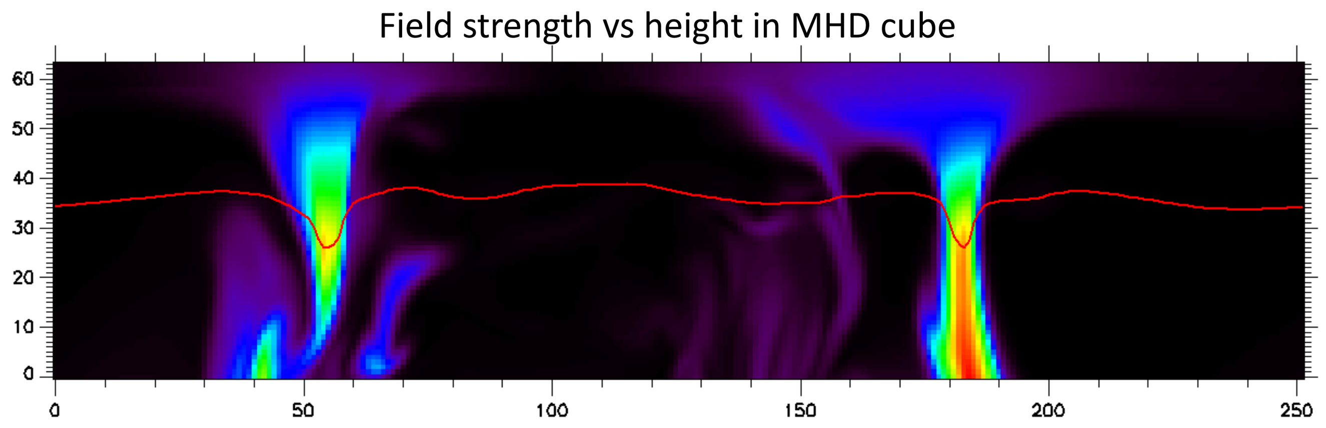
Fig 2. The histograms of the B_{LOS} as inferred from various viewing angles (μ=cos θ) is shown in top panel where μ is color coded. The number of pixels measuring stronger flux reduces systematically as is expected for the case of predominantly vertical flux tubes in intergranular network region. Traditionally, 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 is shown in the bottom panel.

Results:

The mean magnetic flux in solar polar regions inferred from LOS magnetographs is underestimated due to multiple 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 $B_R=B_{LOS}/\mu$. This has following implications:



- Flux tubes are vertical only in the darkest intergranular lanes, flux tube expands outside this region to form a magnetic canopy.
- The canopy fields have a pseudo-bipolar appearance away from the disk center, just like unipolar round sunspots appear pseudo-bipolar when viewed away from the disk center.
- 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.)
- Doing spatial average (over polar regions) of the pseudo-bipolar canopy flux leads to flux cancellation and hence an underestimation of the polar flux.
- Changing B-angle of the Sun from 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 the disk center, as compared to inclined LOS which effectively samples progressively upper layers with viewing angle.

Conclusions:

(i) LOS samples progressively upper layers of the flux tube atmosphere where the magnetic configuration is no longer dominantly vertical but more of a canopy-like configuration.

(ii) The deep-rooted stronger vertical flux remains obscured/poorly viewed from the inclined LOS. Unfortunately, the approximation $B_R=B_{LOS}/\mu$ is only valid for this vertical part of the flux tube.

(iii) The inclined view samples the canopy region of flux tube 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.

(v) Out of ecliptic observations, such as from polar flyby orbit proposed for Solaris mission, would help to resolve the true polar magnetic flux.