Estimating the Radial Field Component from LOS Magnetograms:

A Practical Pipeline and Case Study for the September 5, 2022 Backside Event

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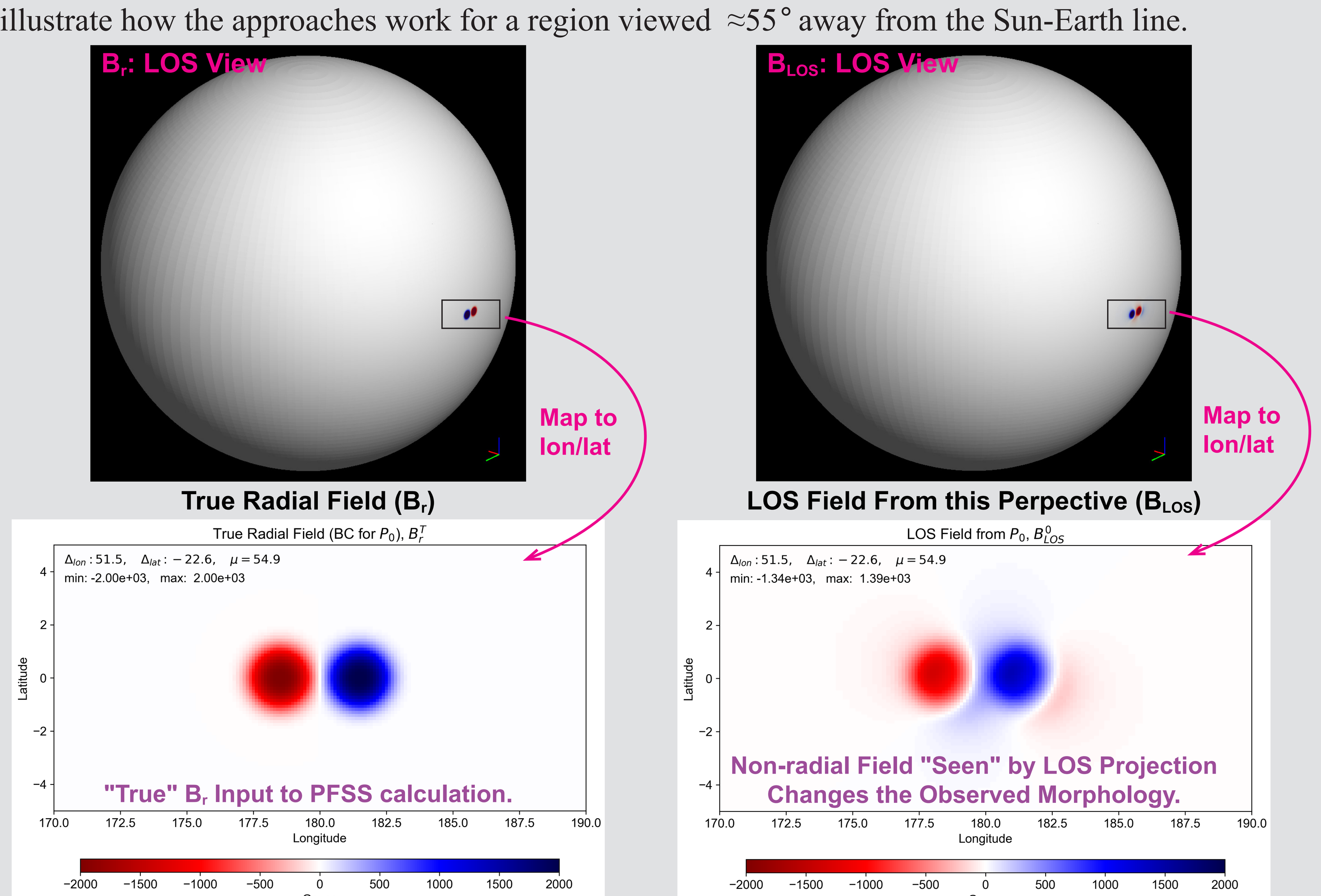
Abstract

The key observational input for data constrained models of the solar corona is the boundary condition for the normal component of magnetic field, Br, at the coronal base. Frequently, Br is derived from LOS magnetograms or maps, as these are often the most easily (and sometimes only) accessible data. Typically, Br is derived from the LOS component of the field, Blos, under the assumption that Blos is predominantly radial in the photosphere where it is measured (e.g. Wang & Sheeley 1992). This geometric approximation often performs well in the weaker field regions of the Sun, but it can be a poor approximation in sunspots, where strongly non-radial fields are clearly present. Another option, used in the earliest potential field models (Altshuler & Newkirk 1969) is to use the machinery of 3D potential field extrapolations to derive the Br distribution of the potential field whose LOS projection will match Blos. As illustrated in Leka et al. (2017) this may have important consequences for the strength and structure of the inferred Br in solar active regions (ARs), and is particularly relevant for artifacts that appear in strong field umbral and penumbral regions observed off of the Sun-Earth line. Leka et al. used a spherical harmonic approach.

Here we describe our recent efforts to develop a pipeline for computing the LOS matching potential field using our high-performance finite-difference potential field solver POT3D. Using a simple iterative method we are able to overcome some of the limitations of earlier approaches while adding the flexibility to localize the calculation, e.g., to use the geometric approximation to derive Br in weaker field regions, while imposing the Blos boundary condition in stronger field regions. We illustrate the practical relevance of these considerations by applying the technique to the case that motivated this work, the backside CME event of September 5, 2022. In this case the only available magnetic field measurements of the rapidly evolving source region are LOS magnetograms from the SolO/PHI/FDT instrument, and this region was ~40 degrees away from disk center as seen by SolO at the time of the eruption. By computing the Br boundary condition in various ways, we illustrate how each technique brings along its own set of issues and how these may be partially ameliorated using a hybrid approach with localization. We then explore how solutions for the global coronal field are impacted by these choices, including non-negligible changes to the footprint of open flux and the S-WEB structure. While there is clearly no substitute for vector magnetic field information (when available), we also discuss future applications where this practical technique may be relevant.

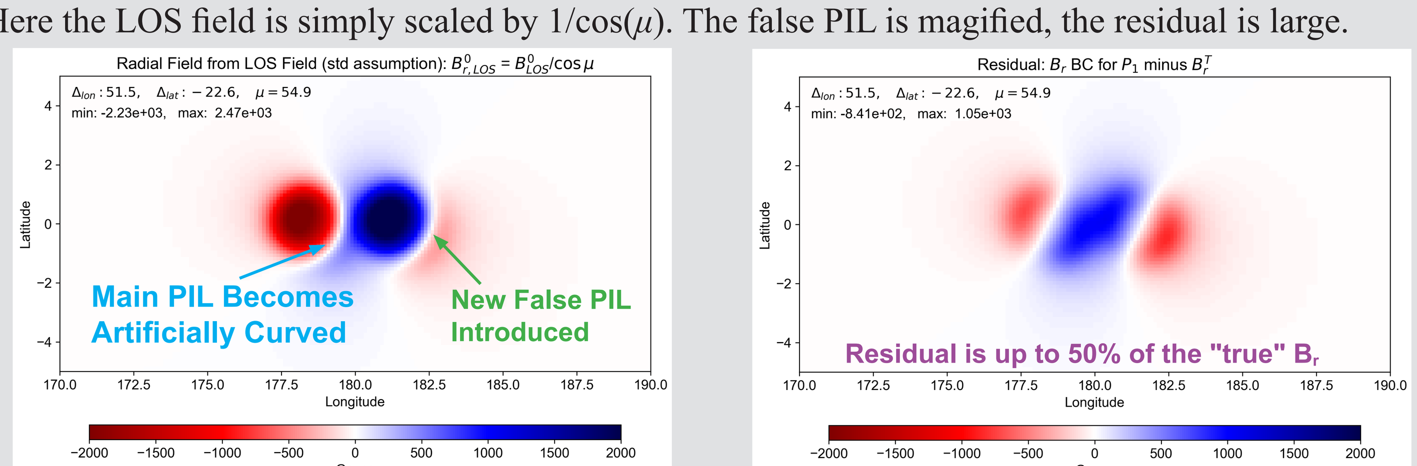
Why Match B_{LOS}? A Motivating Example

- Use a potential field source surface (PFSS) exctrapolation for an idealized bipolar flux distribution to illustrate how the approaches work for a region viewed $\approx 55^\circ$ away from the Sun-Earth line.



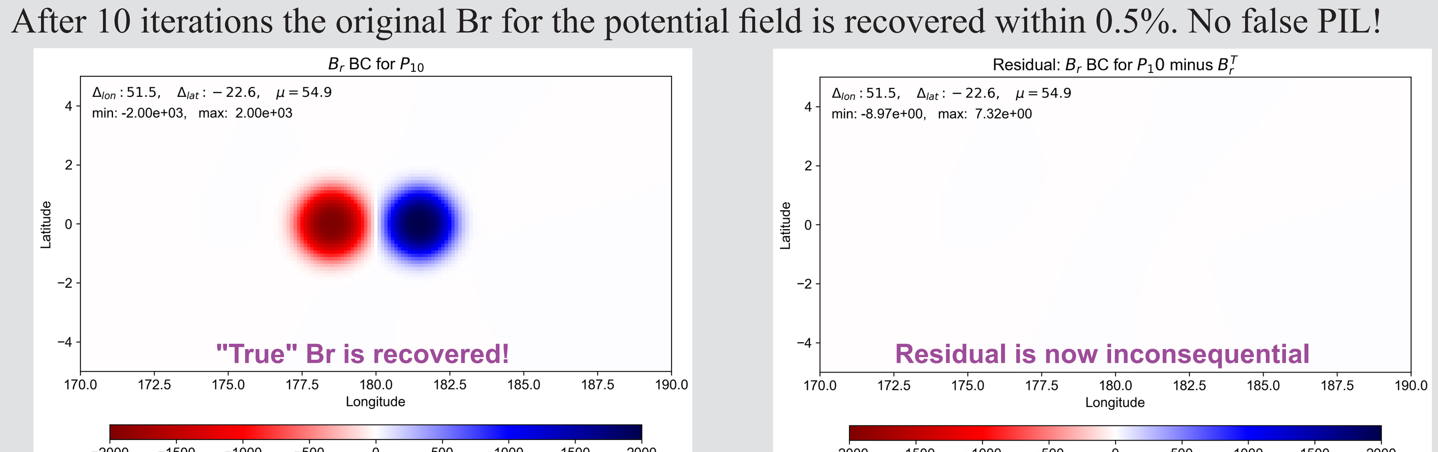
A) B_r from the Standard Radial Assumption

- Here the LOS field is simply scaled by $1/\cos(\mu)$. The false PIL is magified, the residual is large.



B) B_r from B_{LOS} Matching Pipeline

- After 10 iterations the original Br for the potential field is recovered within 0.5%. No false PIL!



Synopsis

- Extrapolations and MHD models of coronal **B** fields generally require, at minimum, knowledge of the normal component of **B** at the lower coronal boundary, B_r.
- This information usually comes from measurements of the surface field, typically in the photosphere.
- If vector field measurements are either 1) not available, or 2) of sufficient quality, then the normal component must be estimated from line-of-sight (LOS) magnetograms, B_{LOS}.
- Depending on the structure being observed, this can lead to incorrect estimations of field strengths and even incorrect polarities that give false polarity inversion lines (PILs).

Estimating B_r from B_{LOS}

- We explore three different approaches for obtaining the normal component of B from LOS magnetograms.

A) *Radial Assumption*

- By far the most common solution to this problem is to assume that the "true" field sampled by the LOS magnetogram is purely radial. In this case B_r can be determined from simple geometry by using the center-to-limb angle.
- This is well justified in places where the fields are tightly collimated in the photosphere and mostly vertical.

B) *B_{LOS} Matching*

- Another option is to solve for the 3D potential field that matches the LOS magnetogram.
- Here one computes all three components of **B** at the surface subject to the constraint that the LOS projection of **B** matches the observed B_{LOS}. This solve provides B_r directly.
- This approach is more "consistent" with the observations in principle. It can also work better in strong field regions like sunspots. However it may have some undesirable properties in weak field regions.
- One way to compute the B_{LOS} matching potential field is to use the machinery of spherical harmonics (e.g. Altshuler & Newkirk, 1969; Leka, Barnes & Wagner, 2017).
- Another option is to solve the problem in an iterative fashion using finite difference methods (this work).

C) *Hybrid Approach (this work)*

- Using an iterative, finite difference approach, it becomes possible to localize where one updates the B_r boundary conditions for each step in the B_{LOS} matching solve.
- This allows one to transition between the Radial Assumption (A) and B_{LOS} Matching (B) subject to some criteria.
- Here we use a smooth mask, $M(|\mathbf{B}|)$, to transition between strong and weak field regions on the surface.
- This can possibly provide a "best of both worlds" solution.

Iterative Pipeline for B_{LOS} Matching

Goal: Solve for the potential field that matches B_{LOS}.

Tool: POT3D

- An open source, high-perfomance, 3D potential field solver.
- Finite difference solver, multiple options for grid and outer BCs.
- Parallelized for multi-CPU, multi-GPU, or hybrid architectures.
- Open source: github.com/predsci/POT3D

Algorithm: Brute force iterative loop of 3D potential solves. Final solution in minutes on four GPUs.

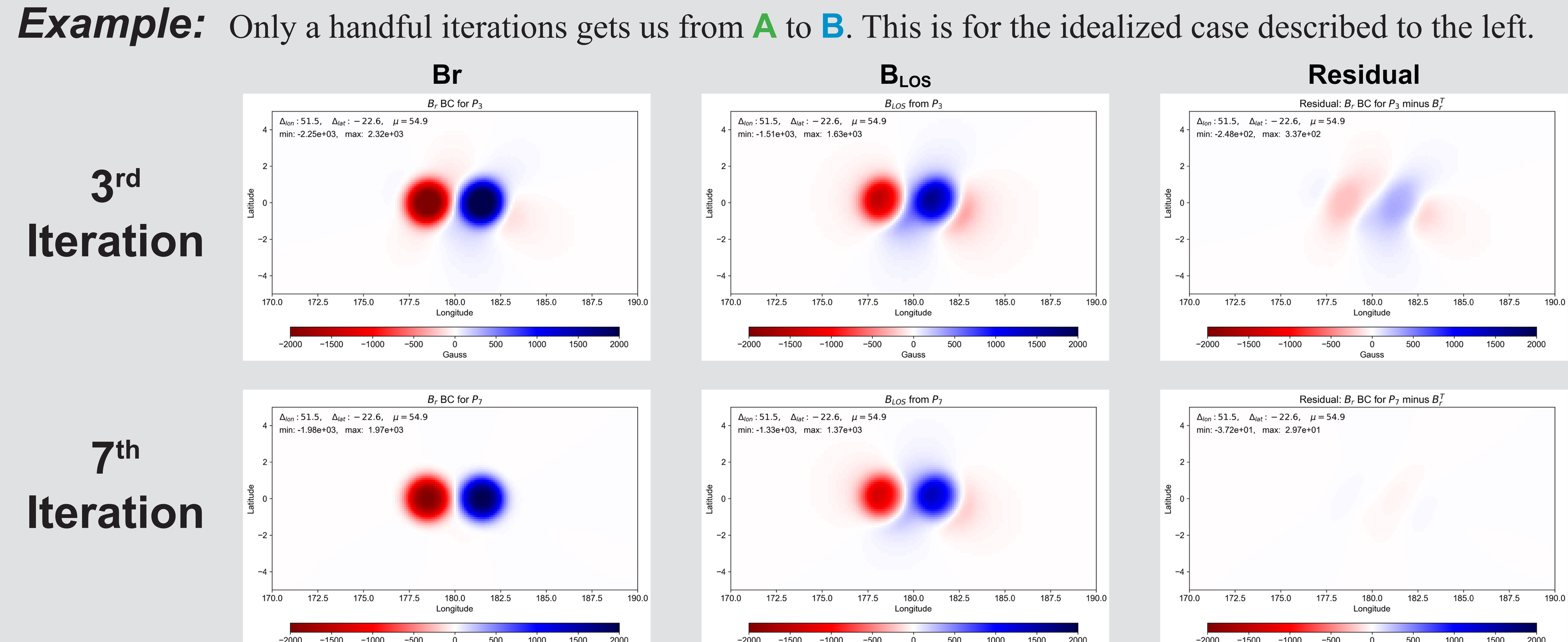
Initialization: Create a full-sun B_r map using the Radial Assumption (A).

LOOP

1 Solve: Compute a 3D potential field using B_r.
2 Project: Project the new **B** at the surface along the LOS to get B_{LOS} at this step.
3 Compare: Compute the LOS residual, $R^i = M^i(B^i_{LOS} - B^{Obs}_{LOS})$, where M is a localization mask.
4 Update: Update the B_r map for next solve by adding the residual: $B^{i+1}_r = B^i_r + R^i$.

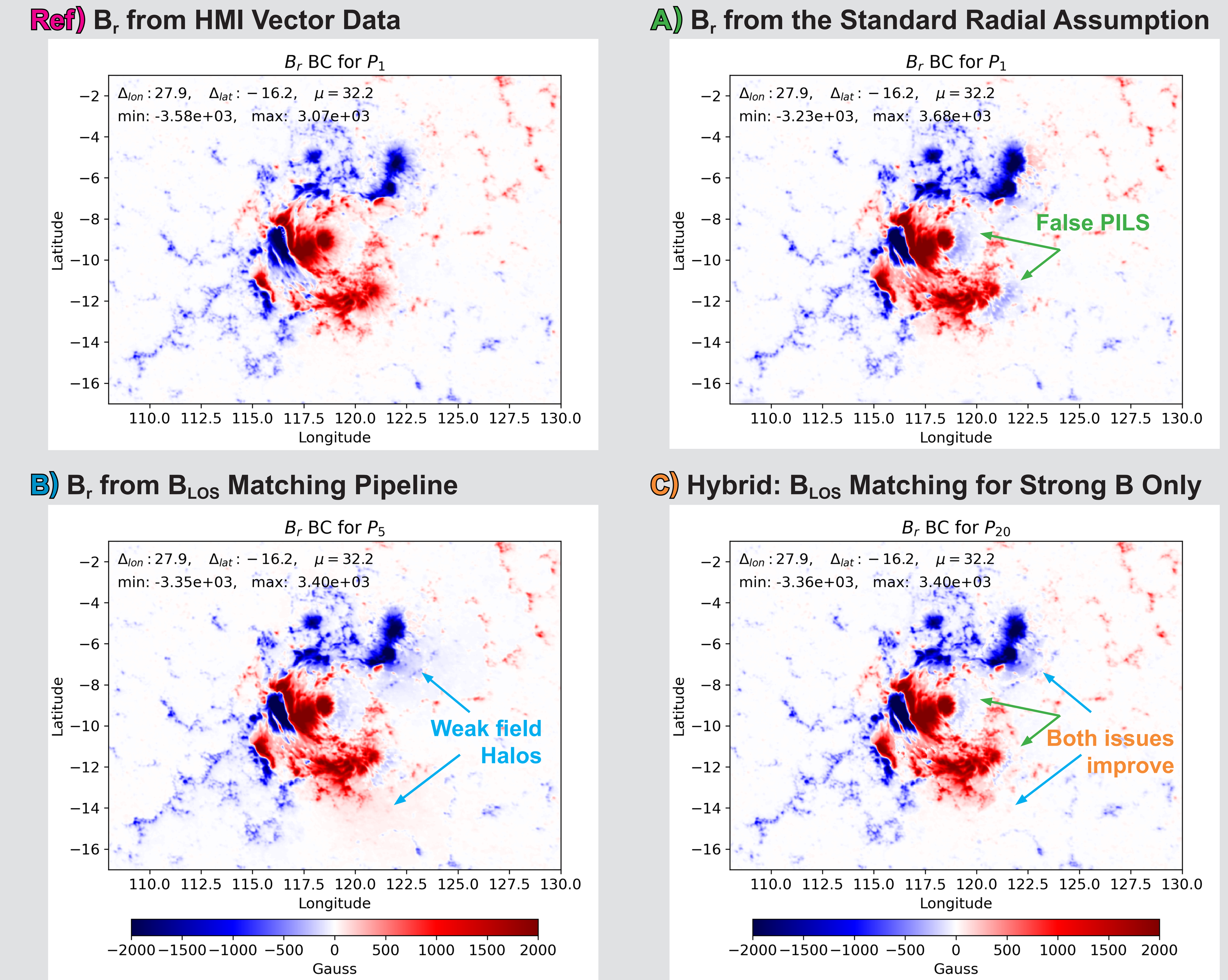
Finish: End when stopping criteria for the residual is met. e.g when B_{LOS} matches better than 0.5%.

Example: Only a handful iterations gets us from A to B. This is for the idealized case described to the left.



Practical Application 1: HMI Data - Sep 5 2017

- The SDO/HMI data pipeline provides both vector and LOS field measurements.
- Using B_r derived from vector data as the "reference", we can compare approaches for estimating B_r from B_{LOS}.
- Here we try a large complex AR seen $\approx 32^\circ$ off the Sun-Earth line: AR 12673 on Sep 5, 2017 at 20:00 UT.

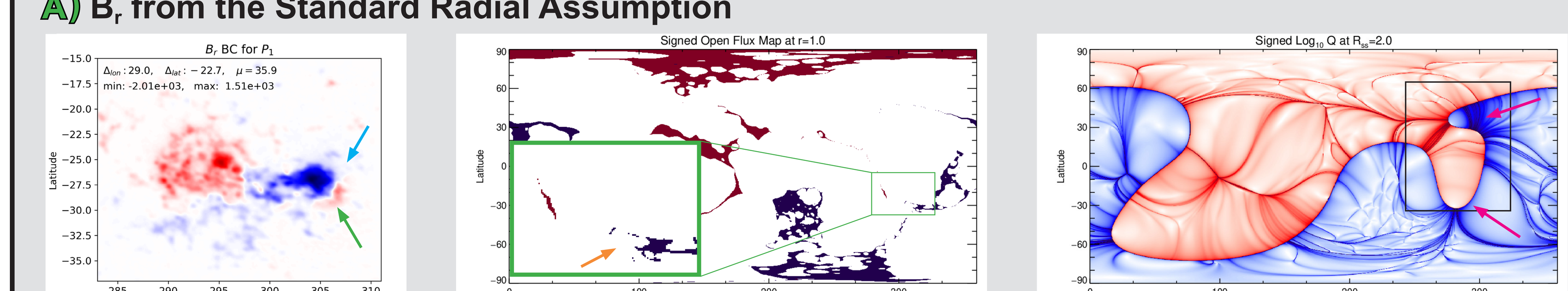


- B Improves the false PIL issue in A, but it is not gone. Also B introduces a non-zero halo in the weak fields.
- C eliminates the weak field halo but otherwise retains the structure of B (great!).
- There is no free lunch! If the surface **B** is non-potential, matching B_{LOS} with a potential field can only do so much.

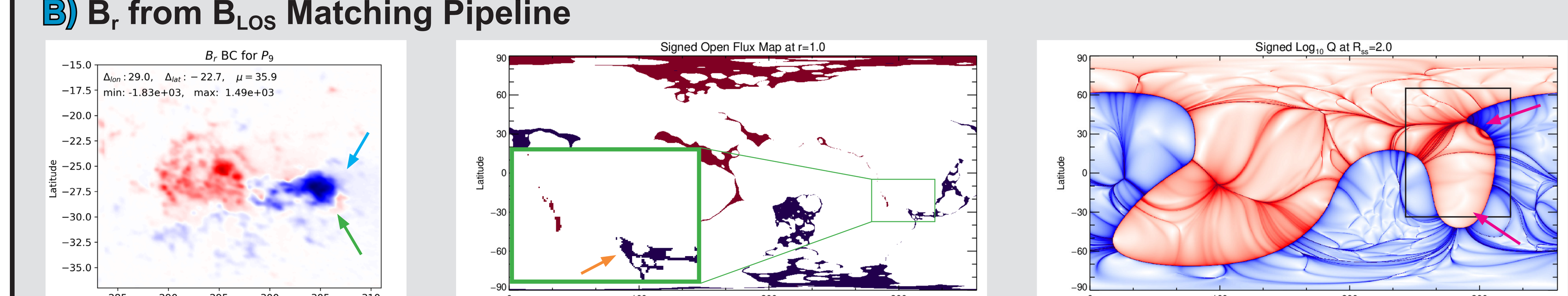
Practical Application 2: SolO/PHI - Sep 5 2022

- On Sep 5, 2022 ≈15 UT, Solar Orbiter and PSP observed a fantastic CME on the backside of the Sun from Earth.
- We wish to model the event, but currently only LOS magnetograms are available from the SolO/PHI instrument.
- The source region's magnetic morphology was rapidly changing before & after the CME, so we wish to use B_{LOS} measured just prior to the event. At 4 UT, the AR was south and east, $\approx 36^\circ$ off the Sun-Earth line at this time.

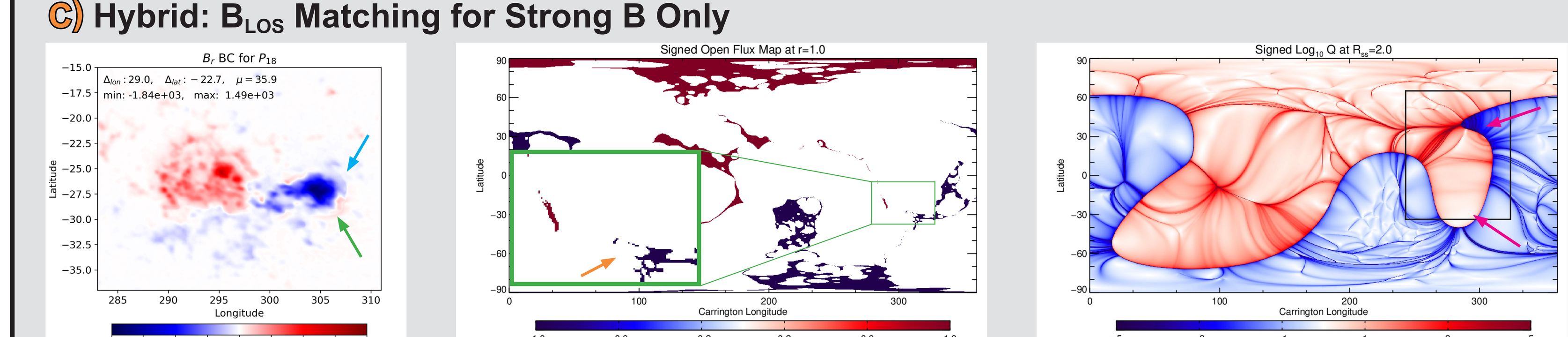
A) B_r from the Standard Radial Assumption



B) B_r from B_{LOS} Matching Pipeline



C) Hybrid: B_{LOS} Matching for Strong B Only



- As before, B Improves the false PIL issue in A. We also see the pattern of open flux near the region is slightly changed from A to B, as is the shape of the HCS at the source surface at 2.0 R_s.
- C eliminates the weak field halo. Open flux is mixture of A and B, but the HCS pattern is similar to B (great!).
- There is no substitute for vector data, but how one estimates B_r from B_{LOS} has consequences for the solution!