Overview of The 180° Ambiguity in Solar Vector Magnetic Field Measurements and Present Methods for Solving It

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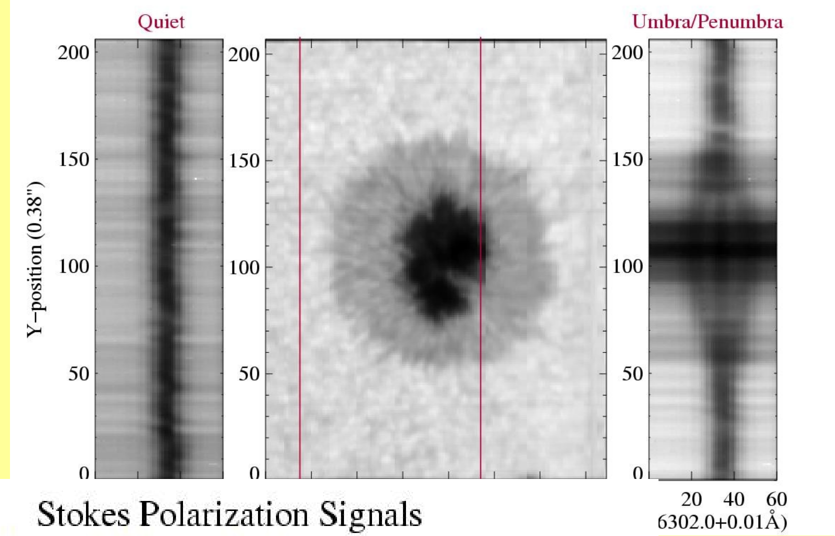
- **Early synoptic instruments made it v*ery* clear *very* early on that *automated* data-reduction algorithms were required, *including ambiguity resolution.***
  - U.Hawai`i's Haleakala Stokes Polarimeter,
  - Imaging Vector Magnetograph;
  - NAOJ/Mitaka's Flare Telescope,
  - MSFC's vector magnetograph, BBSO's video magnetograph.
  - Observer-driven instruments: less data and less automation needed. Human-based interactive approaches were possible.

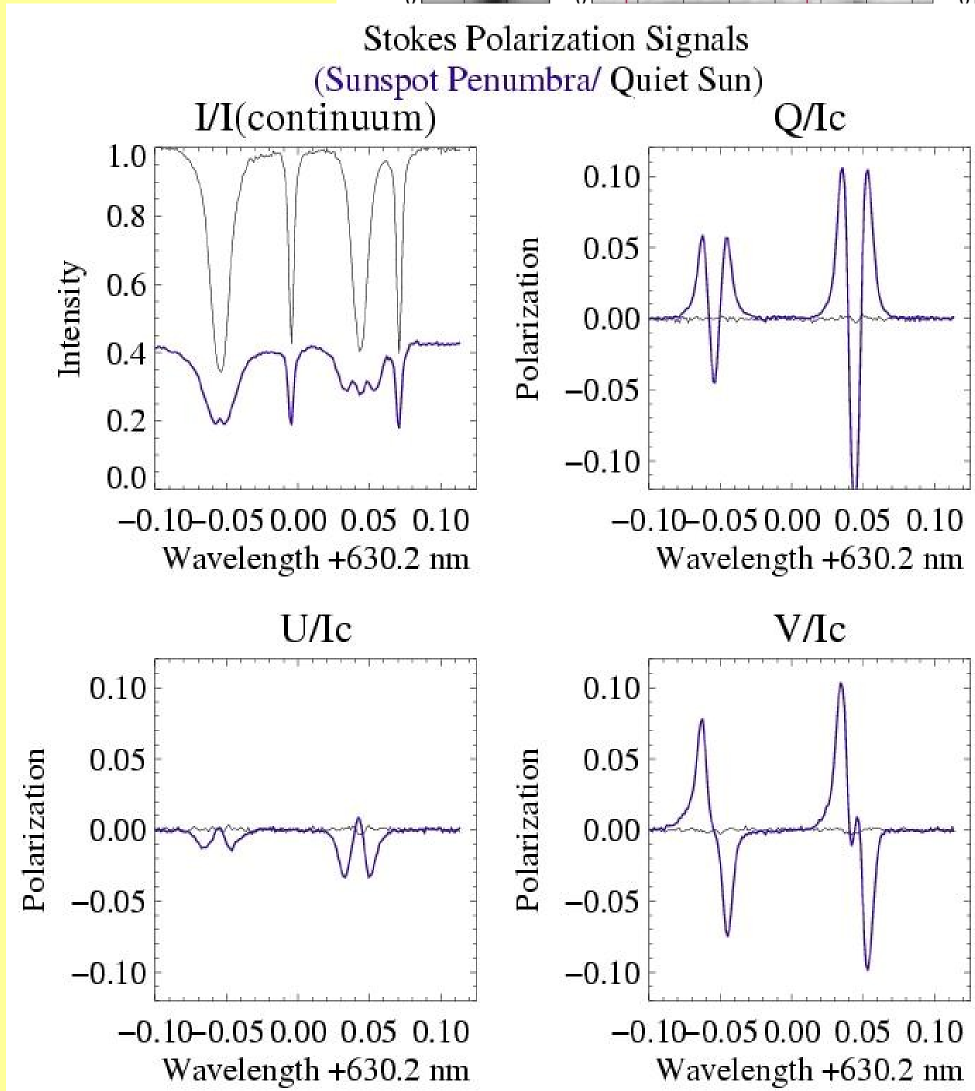
- With high-resolution and high-cadence data (Hinode, ATST, SDO/HMI, SOLIS), algorithm(s) are required with high ***performance value*** (courtesy C. Henney):
  - *Accurate enough for science goals*
  - Stable for conditions of interest (e.g. Full-disk)
  - Fast relative to inversion time,
    (define Time= InversionTime / AmbigTime)
  - Is the algorithm automatic?
    If yes, (set Auto= 1, otherwise Auto= ∞)
  - **Merit = (% accuracy * Stability + Time) / Auto**

Measuring the photospheric magnetic field:

Stokes spectropolarimetry:

- Zeeman effect: magnetic field induces both energy-level splitting and polarization to emergent light of magnetically sensitive lines.
- Splitting proportional to $|\boldsymbol{B}|$:
- Split components are polarized:
  - For B⊥: π components are polarized parallel to B⊥ , σ components are polarized perpendicular to B⊥
  - For B‖: π components are not visible, and σ components are circularly polarized.
- Final shape of polarization spectra and degree of polarization due to: strength, direction of magnetic field, thermodynamics of plasma, spatial and spectral resolution.
  - Quick reference:
    - B‖: ≈ V
    - B⊥: $\approx (Q^2 + U^2)^{1/2}$
    - $\Phi \approx \tan^{-1}(U/Q) \rightarrow -90° < \Phi < 90°$

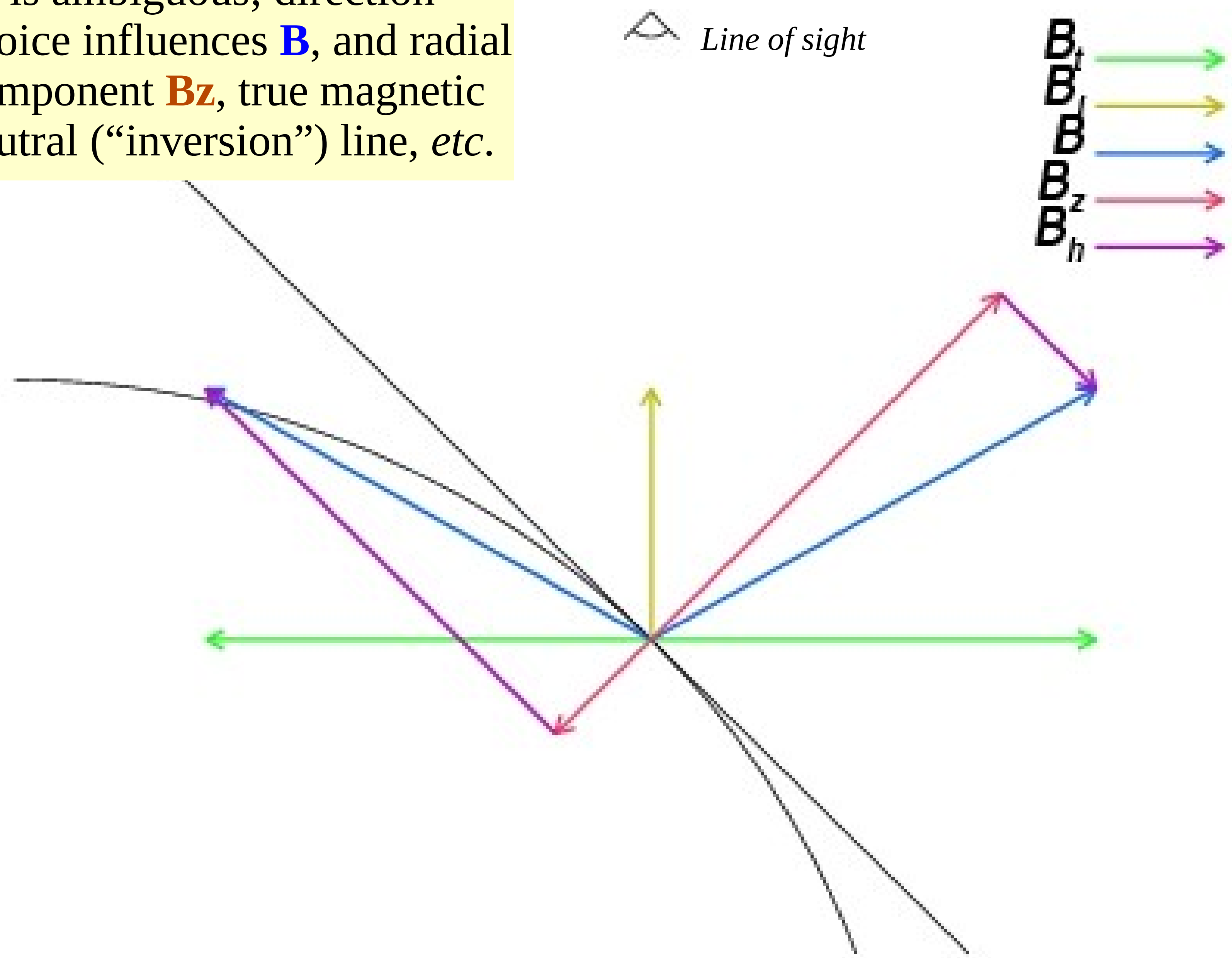




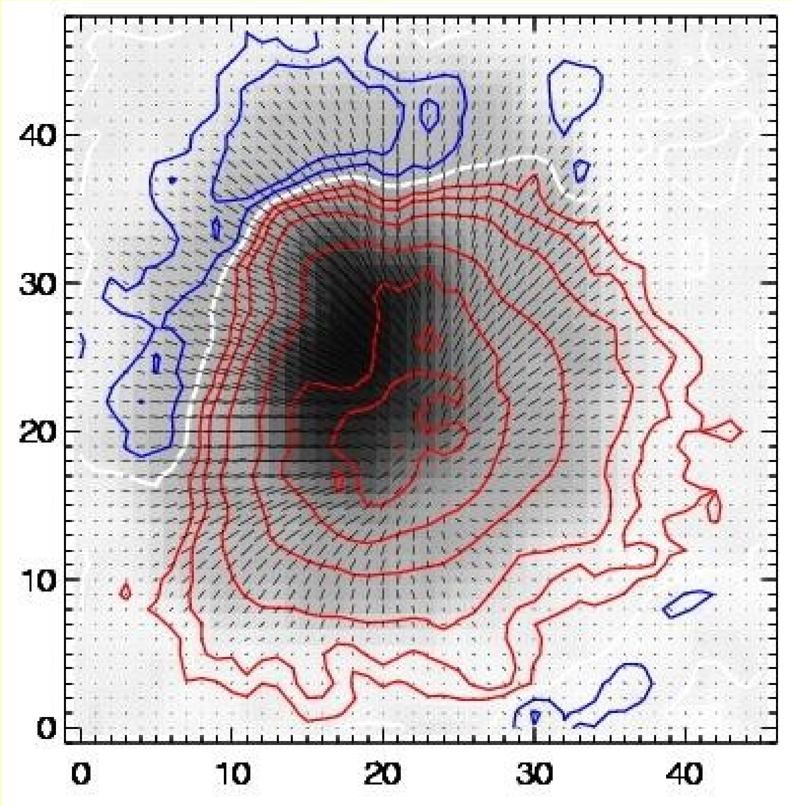
B_{trans} direction is chosen

↓↓↓↓↓↓↓

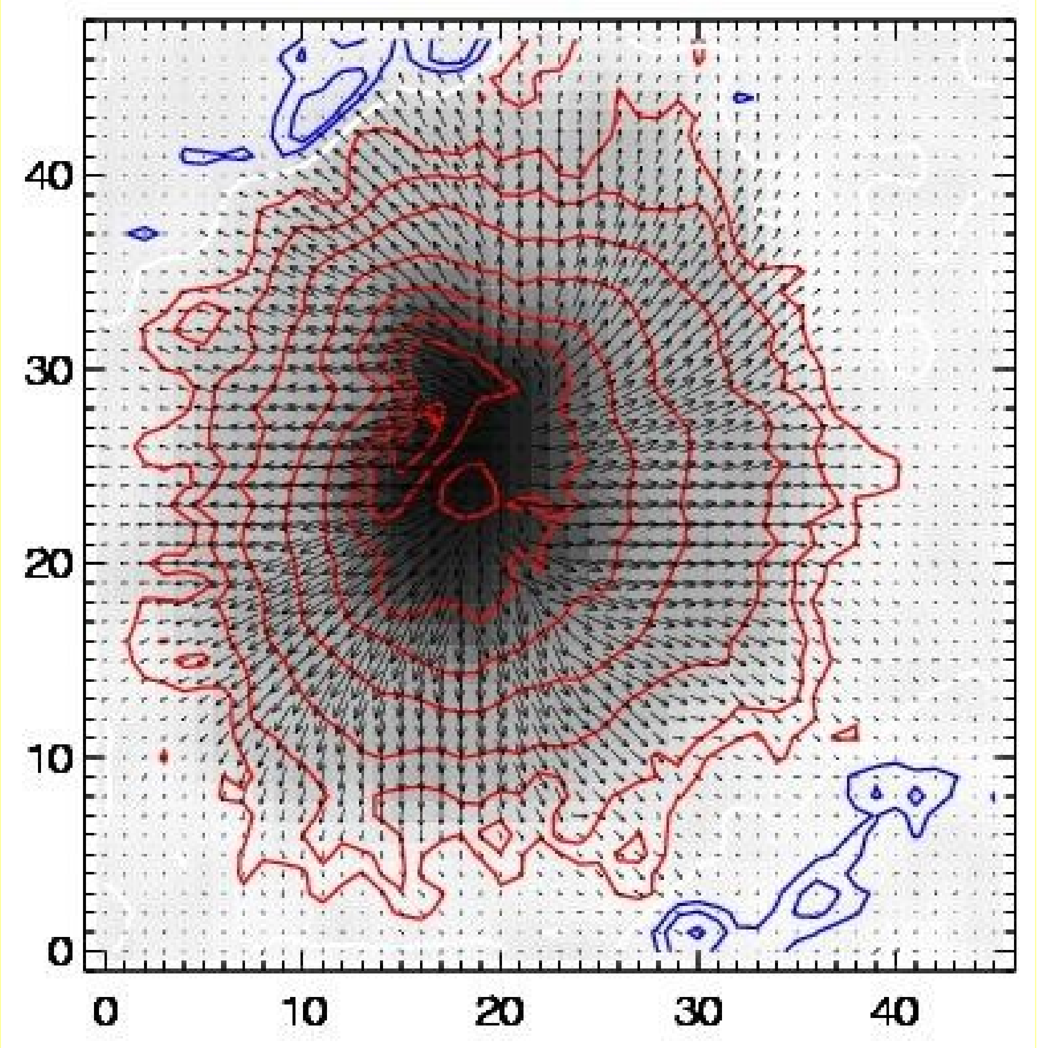
Bt is ambiguous; direction choice influences **B**, and radial component **Bz**, true magnetic neutral (“inversion”) line, *etc*.



- *Results are only physical* after ambiguity resolution and expressed as heliographic ***B***

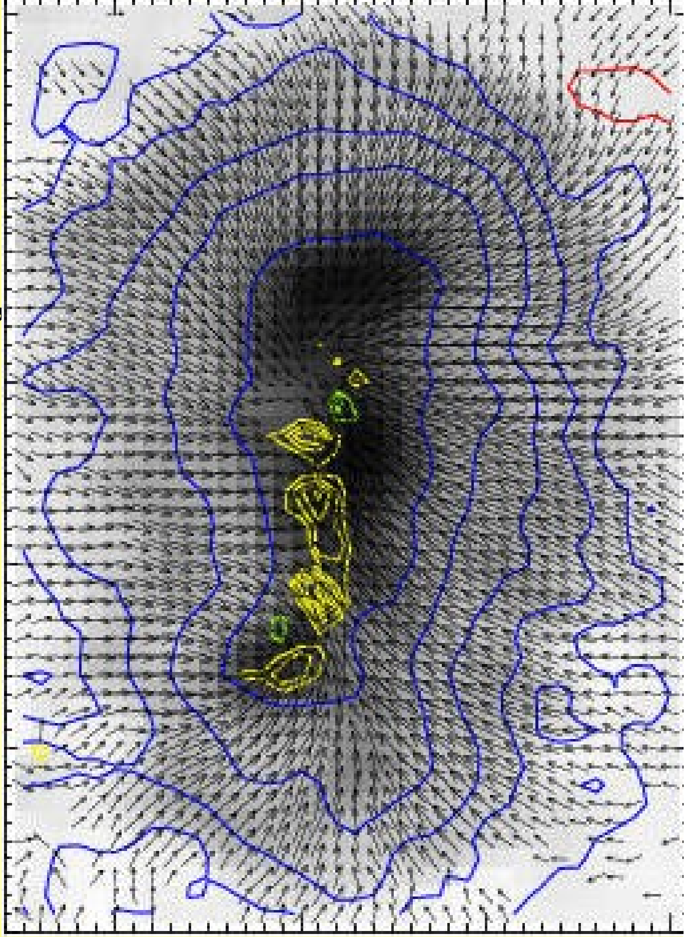


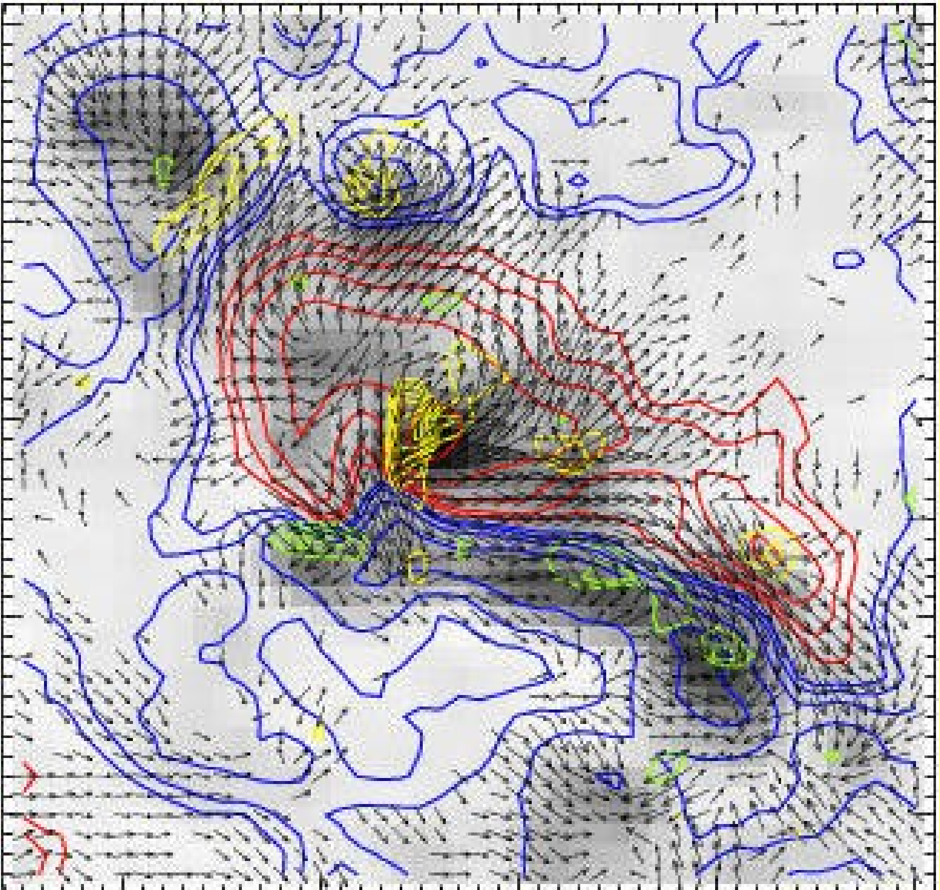
Heliographic *B* results, azimuth resolved (note shift in neutral line)



- Significant differences between $\boldsymbol{B}^i$ and $\boldsymbol{B}^h$ can be observed as little as 10° from disk centre.

- **Simple (and very common) approach: potential-field acute-angle comparison**
  - Compute a potential field using the B_{los} as boundary
  - choose azimuth to be closest to computed potential field, i.e. require $\mathbf{B_t^{pot}} \cdot \mathbf{B_t^{obs}} > 0$
  - Fast for planar approximation (use FFTs)
  - Good for simple, round sunspots
  - Not so good for complex regions.





Both images: red/blue contours of +/- radial magnetic field, arrows of horizontal field, green/yellow contours of +/- vertical current density.

- *More sophisticated algorithms needed for non-potential active regions, for example:*
  - Initial resolution based on potential *or constant-α force-free* fields.
  - Iterate, minimizing:
    - vertical currents
    - the divergence
    - angle between neighboring pixels
    - other appropriate function

- ***All methods follow same two steps:***
  - Assume a model field
  - Choose the azimuth which best matches the model field: $\boldsymbol{B_t}^{\boldsymbol{model}} \cdot \boldsymbol{B_t}^{\boldsymbol{obs}} > 0$
- ***Differences come in model chosen,....***
  - Potential field, non-potential field
    - There are different ways to compute a potential field....
  - Same at all scales? Or a different model for large- and small-scale structures?
  - Most consistent with ____________ (div(B)? Jz=0? Multi-fractal?)
- ***... and how to implement "best match".***
  - Manually evaluate ("by my eye")
  - Iteratively pixel-by-pixel with (or without) neighboring pixel results?
  - Optimize a global function
  - Down-hill gradient, Multi-dimensional conjugate gradient,
  - Genetic, Amoeba, others....

Just a few different approaches:

- **Potential-field acute-angle**
  - Using *FFTs* (K. Leka, J. Jing) with/without flux balance, boundary padding
  - Based on *Green's Function solution* (J. Li, V. Yurchyshyn)
- **Large-Scale Potential method** (A. Pevtsov)
  - assumes large-scale fields are potential, deviations increase with spatial resolution
- **Linear Force-Free Acute-Angle method** (H.N. Wang)
  - Best-fit to LFFF field consistent with coronal-loop observations
- **Uniform Shear Method** (Y.J. Moon)
  - assumes shear angle follows a normal distribution
- **Magnetic Pressure Gradient** (J. Li)
  - assumes magnetic pressure decreases with height
- **Minimum Structure** (M. Georgoulis)
  - Minimize a component of current analytically, then numerical smoothing
- **NonPotential Magnetic Field Calculation** (M. Georgoulis)
  - Finds the distribution of Bz whose potential extrapolation plus a calculated non-potential component best matches the observed heliographic field.
- **Pseudo-Current Method** (A. Gary)
  - Minimizes J_z^2 by locating sources of non-potentiality
- **U. Hawai`i Iterative Method (Metcalf, Fan & Leka)**
  - Iterates locally to minimizes Jz and div(***B***), then acute-angle neighbor smooths
- **Minimum-Energy solution (Metcalf)**
  - Global optimization of *J* and div(***B***), numerous weighting options

Summary

- Ambiguity resolution a *necessary evil* for full utilization of vector magnetic field data
- Evaluating is really only possible using sophisticated “hare and hound” approaches to test recognized failure modes.
- A method *must* perform better than potential-field acute-angle algorithms to have value.
  - Caveat: there are differences even between potential-field methods!
- Additional requirements (stability, automation) to evaluate ***merit***
- *Metrics* required for inter-comparison
  - Good metrics are easy to understand intuitively, and provide distinguishing information, and *can be difficult to construct* in some cases.
- All methods presented here make assumptions about the solar magnetic field. Using height information to ensure $\nabla \circ \mathbf{B}=0$ removes assumptions.
- Best algorithm may depend on data source and question being asked.

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