Tracking Vector Magnetic Fields

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Motivation

- Incorporate plasma physics into solar motion estimation: Analyze vector magnetograms with ideal MHD
- Determine 3D photospheric plasma velocities
- Test CME initiation models that require neutral line footpoint shearing
- Quantify the magnitude and timing of energy and helicity fluxes in active regions
- Provide boundary conditions for MHD simulations of the corona

Optical Flow Models

***Caveat Emptor*!**

- The velocities estimated from optical flow techniques *depend* on motion model applied
  - **All** velocity estimation algorithms have an underlying motion model
  - Even Local Correlation Tracking (LCT) has an assumed motion model: advection in a uniform flow.
- If the images do not satisfy the motion model, the methods will produce (at best) biased results due to model misspecification.
  - The results may not be simply related to local plasma velocities and the onus is on the user to “interprete” these estimates.
  - These “velocities” may be *still* be useful for empirical image processing, i.e., image segmentation.

Optical Flow Models

- Local Correlation Tracking (for small displacements)

$$C \approx \int d^2x \overbrace{w\left(\chi - \boldsymbol{x}\right)}^{\text{Aperture}} \left[\overbrace{\partial_t I_n\left(\boldsymbol{x}, t\right) + \widehat{\boldsymbol{u}}_0 \cdot \boldsymbol{\nabla} I_n\left(\boldsymbol{x}, t\right)}^{\text{Advection Equation}} \right]^2$$

- Differential Affine Velocity Estimator (DAVE)

$$C \approx \int d^2x w\left(\chi - \boldsymbol{x}\right) \left\{ \partial_t n\left(\boldsymbol{x}, t\right) + \boldsymbol{\nabla} \cdot \left[n\left(\boldsymbol{x}, t\right) \left(\widehat{\boldsymbol{u}}_0 + \widehat{\boldsymbol{W}} \cdot \boldsymbol{x} \right) \right] \right\}^2$$

$$C \approx \int d^2x w\left(\chi - \boldsymbol{x}\right) \left\{ \partial_t n\left(\boldsymbol{x}, t\right) + \left(\widehat{\boldsymbol{u}}_0 + \widehat{\boldsymbol{W}} \cdot \boldsymbol{x} \right) \cdot \boldsymbol{\nabla} n\left(\boldsymbol{x}, t\right) \right\}^2$$

Track the vertical component of ***B*** to produce biased estimates of the horizontal plasma velocities (see *Caveat Emptor*).

Optical Flow Models

- Differential Affine Velocity Estimator for Vector Magnetograms (DAVE4VM)

$$C \approx \int dx^2\, w\,(\boldsymbol{x} - \chi) \left\{ \partial_t B_z\,(\boldsymbol{x}, t) + \boldsymbol{\nabla}_h \cdot \left[B_z\,(\boldsymbol{x}, t)\; \widehat{\boldsymbol{v}}_h - \widehat{v}_z\, \boldsymbol{B}_h\,(\boldsymbol{x}, t) \right] \right\}^2$$

$$\widehat{\boldsymbol{v}} = \begin{pmatrix} u_0 \\ v_0 \\ w_0 \end{pmatrix} + \begin{pmatrix} \widehat{u}_x & \widehat{u}_y \\ \widehat{v}_x & \widehat{v}_y \\ \widehat{w}_x & \widehat{w}_y \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \qquad \boldsymbol{\nabla}_h = (\partial_x, \partial_y)$$

  - Incorporates both vertical and horizontal magnetic field components
  - 3D photospheric plasma velocities: explicit vertical flows
  - Variational principle results in a least squares/total least squares estimator
    - Can incorporate magnetic field covariance matrices (uncertainties)
  - Pretty fast and efficient: 30 seconds for a 288 $\times$ 288 image (in IDL) and should be faster in parallel Fortran

Optical Flow Models

Main Difference(s) Between DAVE & DAVE4VM

- DAVE implements the Démoulin & Berger (2003) assumption that tracking the vertical component of $\boldsymbol{B}$ is equivalent to tracking the footpoint velocity (or flux transport velocity) $\boldsymbol{u}$

$$\partial_t B_z + \nabla_h \cdot (\boldsymbol{u}\, B_z) = 0 \qquad \boldsymbol{u}\, B_z \Longrightarrow \boldsymbol{v}_h\, B_z - v_z\, \boldsymbol{B}_h$$

- DAVE4VM independently estimates the horizontal and vertical plasma velocities (and shears) and computes the footpoint velocity from these

$$\partial_t B_z + \nabla_h \cdot (\boldsymbol{v}_h\, B_z - v_z\, \boldsymbol{B}_h) = 0 \qquad \boldsymbol{v}_h\, B_z - v_z\, \boldsymbol{B}_h \Longrightarrow \boldsymbol{u}\, B_z$$

- Démoulin & Berger assumption equivalent to $\boldsymbol{B}_h = 0$. Results in biased estimates of the horizontal plasma velocity $\boldsymbol{v}_h$ ... not the footpoint velocity $\boldsymbol{u}$.

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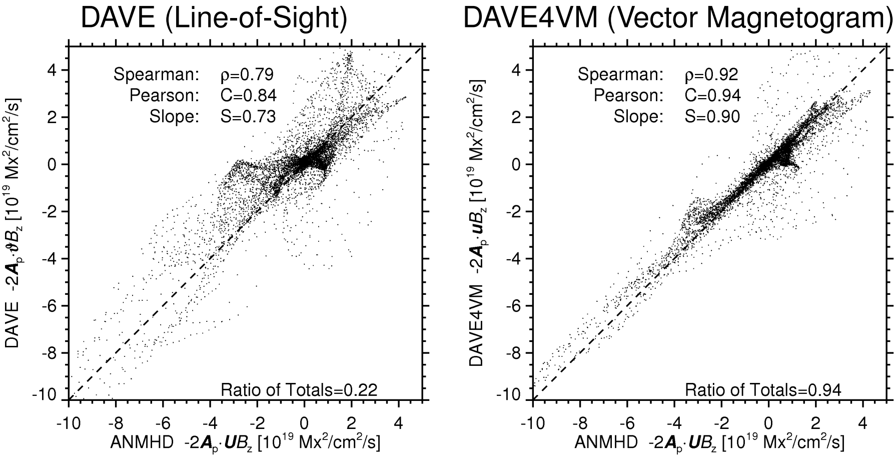
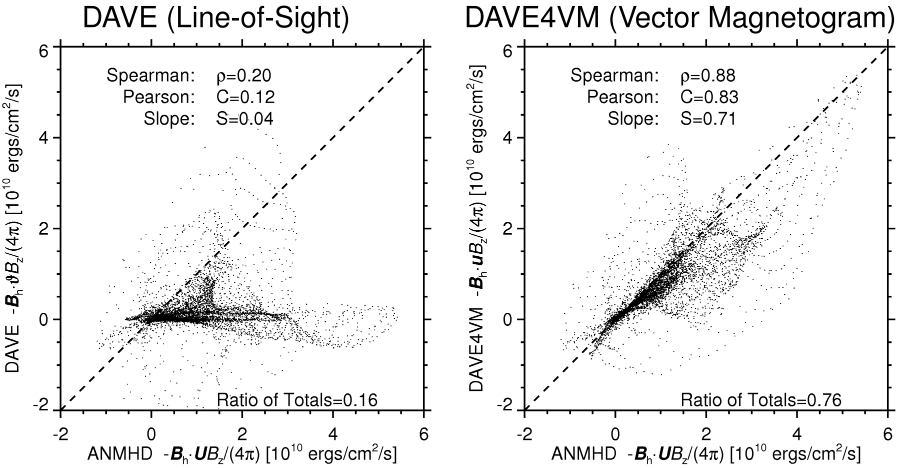
Verification against ANMHD simulations

Helicity and Energy Fluxes



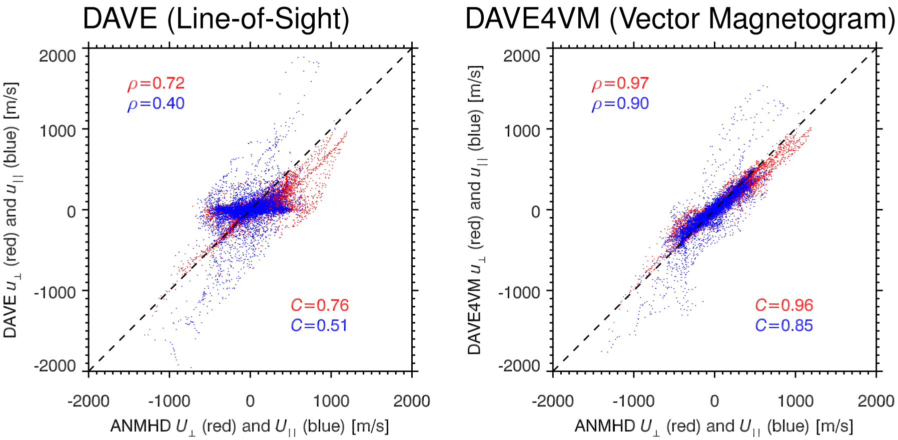
- Constrain the timing and magnitude of Helicity flux



- Constrain the timing and magnitude of Poynting flux

Verification against ANMHD simulations

DAVE4VM Can Estimate Neutral-Line Shear Flows!

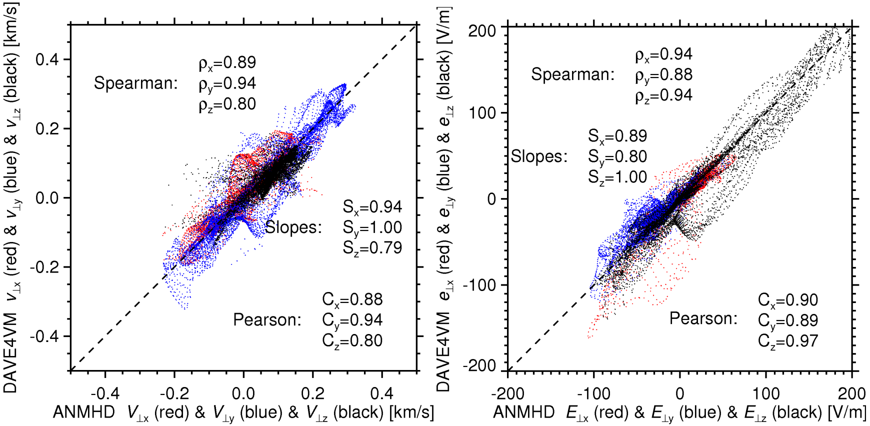


$\perp$ and $\|$ measured relative to contours of B_z

- Constrain CME initiation models

Verification against ANMHD simulations

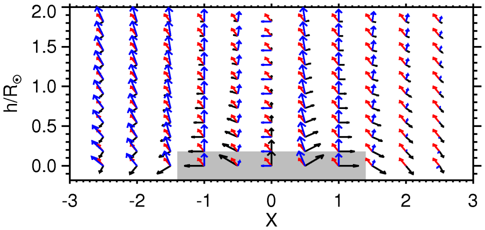
Data products for theory programs



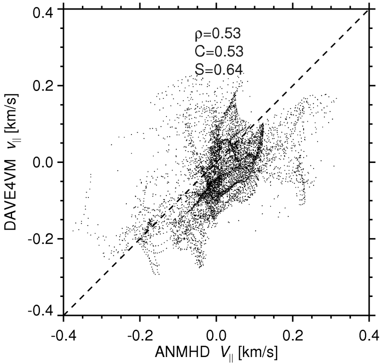
- Boundary conditions (***E*** or ***v***) for simulations CME initiation.

Verification against ANMHD simulations

DAVE4VM Can Estimate Field Aligned Flows!



Schematic diagram of a uniform plasma flow across a diverging magnetic field above the photosphere at $h = 0$. The black arrows indicate the strength and direction of the magnetic field, the red arrows indicate the the direction of the spatially uniform total plasma velocity $\boldsymbol{v}$, and the blue arrows indicate the magnitude and direction of the perpendicular plasma velocity $\boldsymbol{v}_\perp$. The aperture in the photosphere is indicated by the gray box.



(Schuck, 2008)

Software Status

- IDL Codes: DAVE/DAVE4VM released with ancillary routines and examples/figures from article (Schuck, *ApJ*, **683**, 1134-1152, 2008)
  - Oldest: Archived with ApJ
    `www.iop.org/EJ/abstract/0004-637X/683/2/1134`
  - More Recent: Archived at NRL
    `wwwppd.nrl.navy.mil/whatsnew/dave/index.html`
  - Latest: contact me at NASA – peter.schuck@nasa.gov
- HMI Pipeline Codes: in production, Intel Fortran with C-wrappers, and linked with Intel MKL math libraries with drop-in open source replacements (hopefully).

Planned Improvements

- More verification tests on other MHD codes
- Incorporate Doppler velocities to constrain vertical flows
- Incorporate HMI covariance matrices
- Consider spherical geometry

References I

Démoulin, P., & Berger, M. A. 2003, Sol. Phys., 215, 203

Schuck, P. W. 2008, ApJ, 683, 1134, http://arxiv.org/abs/0803.3472

Welsch, B. T., Abbett, W. P., DeRosa, M. L., Fisher, G. H., Georgoulis, M. K., Kusano, K., Longcope, D. W., Ravindra, B., & Schuck, P. W. 2007, ApJ, 670, 1434