Measuring, Understanding, and Using Flows and Electric Fields in the Solar Atmosphere to Improve Space Weather Prediction

George H. Fisher

Space Sciences Laboratory

UC Berkeley

Electric fields and flows in the solar atmosphere:

- Why should we care?
- How do we find flow fields and electric fields from remotely sensed solar data?
- How could we use electric fields and flow fields on the Sun to improve space weather forecasting?
- Some new developments in determining 3-d electric fields and flows from sequences of vector magnetograms

Electric fields on the solar surface determine the flux of magnetic energy and relative magnetic helicity into flare and CME-producing parts of the solar atmosphere:

$$\frac{\partial E_M}{\partial t} = \iint_{\mathbf{S}} dS\, \hat{\mathbf{n}} \cdot \frac{c}{4\pi} \mathbf{E} \times \mathbf{B} \cong \iint_{\mathbf{S}} dS\, \hat{\mathbf{n}} \cdot \frac{-1}{4\pi} (\mathbf{v} \times \mathbf{B}) \times \mathbf{B},$$

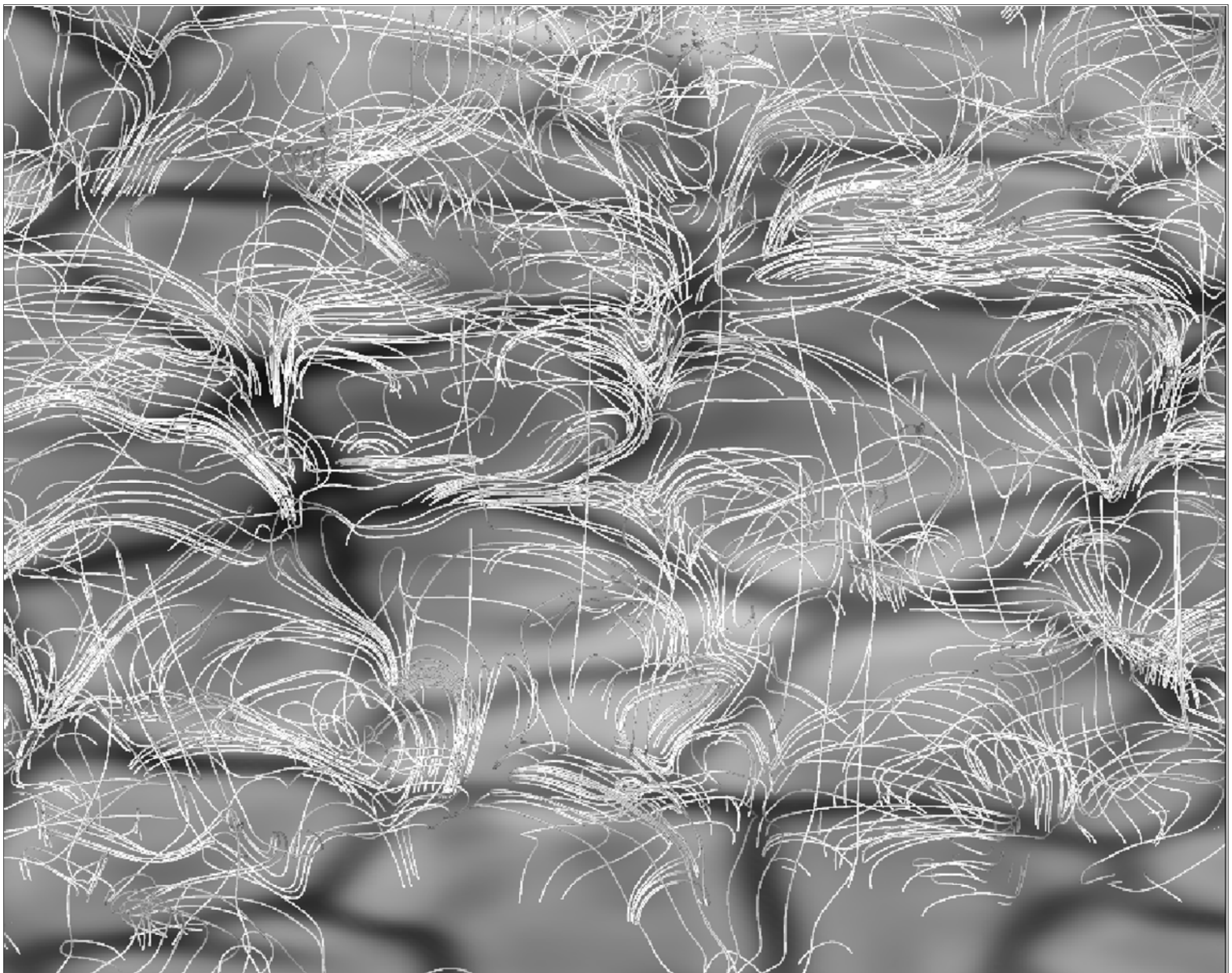
$$\frac{\partial E_F}{\partial t} \cong \frac{1}{4\pi} \iint_{\mathbf{S}} dS\, B_n \mathbf{u}_h \cdot (\mathbf{B}_h^{(P)} - \mathbf{B}_h), \text{ where } B_n \mathbf{u}_h \equiv (\mathbf{v}_h B_n - \mathrm{v}_n \mathbf{B}_h),$$

$$\frac{dH}{dt} = 2\iint_{\mathbf{S}} dS\, \hat{\mathbf{n}} \cdot \mathbf{A_p} \times \mathbf{E} \cong 2\iint_{\mathbf{S}} dS\, \left\{ (\mathbf{A_P} \cdot \mathbf{B_h}) \mathrm{v}_n - (\mathbf{A_P} \cdot \mathbf{v_h}) B_n \right\}.$$

Here, $\partial E_M/\partial t$ is the change in magnetic energy in the solar atmosphere, $\partial E_F/\partial t$ is the difference between the rate of change of total magnetic energy and the potential-field magnetic energy, given a surface distribution of $\mathbf{U}_h$ (Welsch 2006, ApJ 638, 1101), and dH/dt is the change of magnetic helicity of the solar atmosphere.

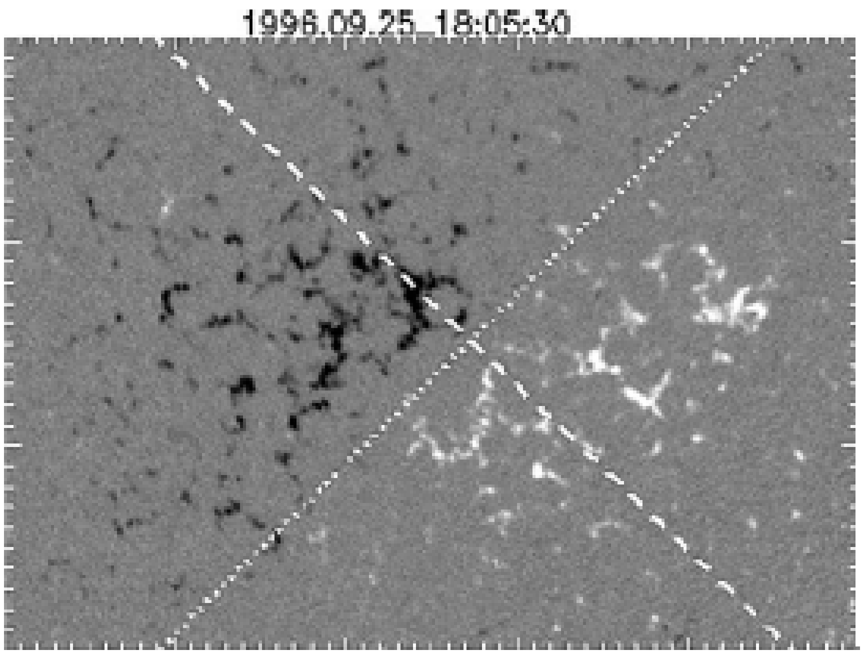
The flow field **v** is important because to a good approximation, **E** =-**v**/c x **B** in the layers where the magnetic field is measured. Here **E** is the electric field, **B** is the magnetic field, and $\mathbf{A_p}$ is the vector potential of the potential magnetic field that matches its measured normal component.

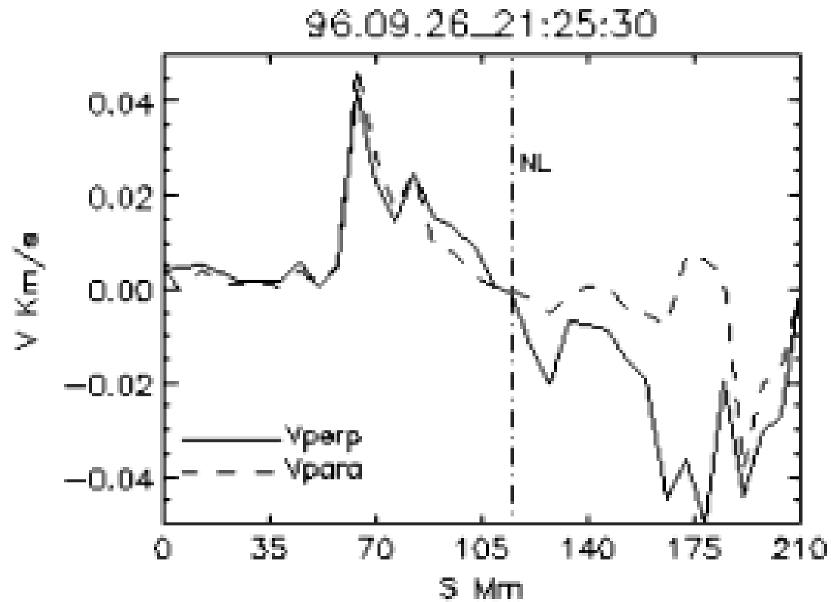
Flow fields and electric fields provide needed physical boundary conditions for data-driven or assimilative MHD models of the solar atmosphere



Measuring the velocity field can help us understand how the magnetic field topology is changing

Li et al. (2004, JATP 66, 1271) studied flows in a CME-productive, decaying active region, finding strong evidence for flux cancellation as the mechanism for the buildup of free magnetic energy in the corona.





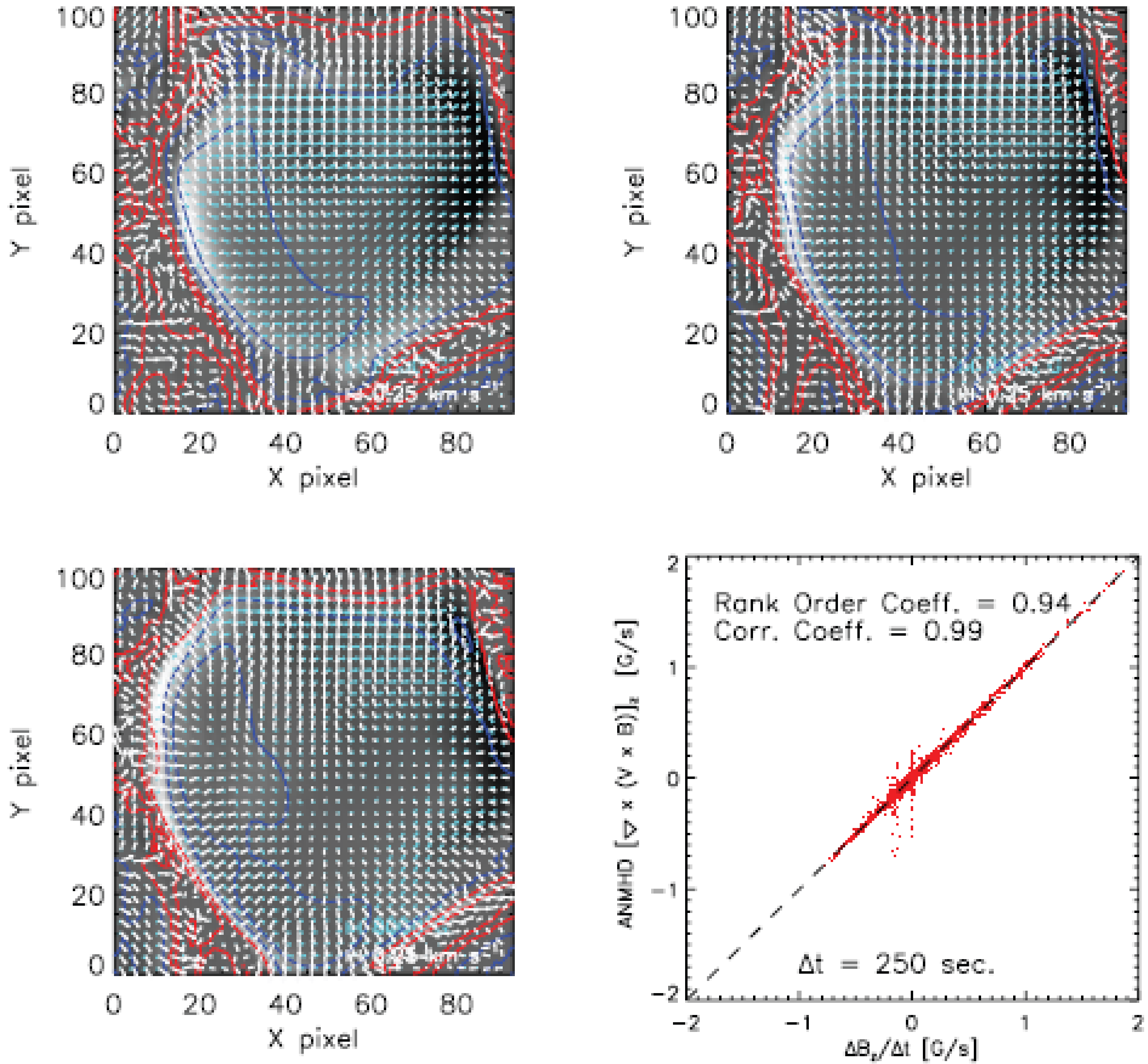
Different velocity inversion techniques:

- Local Correlation Tracking (NSO code, FLCT, LMSAL, Chae 2000) – no information about vertical component of velocity can be derived. Uses localized cross-correlations or error residuals between two images to determine an effective horizontal flow field. No physics included.
- Inductive approach (use vertical component of induction equation to “fix” LCT results, so that normal component of induction equation is solved. – IM, ILCT)
- Global variational approach (MEF, MEF+LCT+Doppler) minimizes a functional while obeying normal component of induction equation.
- Local LSQ Fitting Techniques to solve induction equation (DAVE, DAVE4VM)
- Other techniques: Feature tracking, MSR

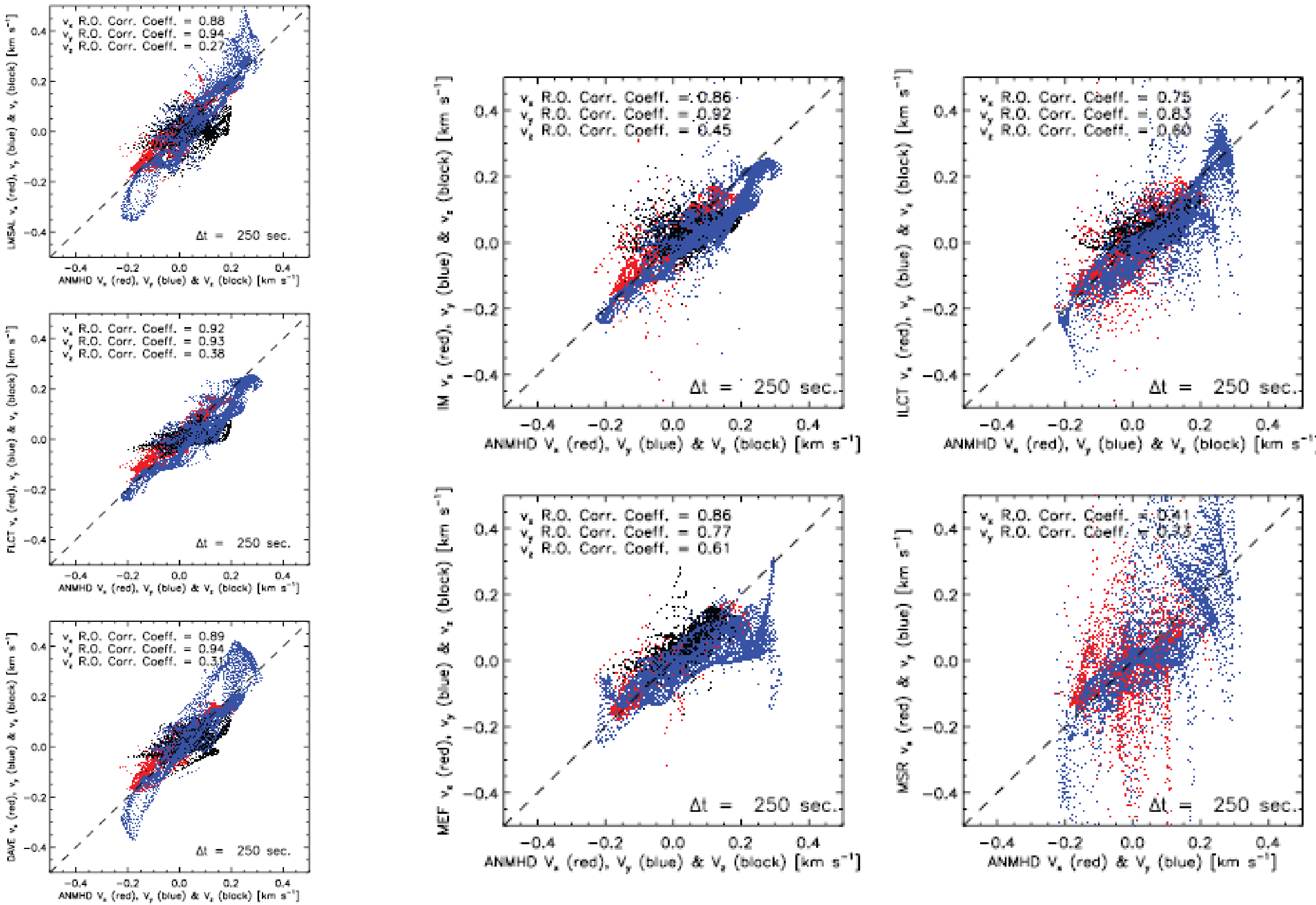
Links where some of these codes can be obtained:

FLCT, ILCT:
http://solarmuri.ssl.berkeley.edu/overview/publicdownloads/software.html
MEF: http://solar.physics.montana.edu/dana/mef
LMSAL: contact Dr. Mark DeRosa (derosa at lmsal dot com)
DAVE: http://wwwppd.nrl.navy.mil/whatsnew/dave/index.html

Velocity inversion shootout: the validation dataset



The shootout: how well do we do?



Shootout: calculation of the helicity flux:

Method	N (pixels)	dH_θ/dt[a] ($Mx^2\ s^{-1}$)	dh_θ/dt ($Mx^2\ s^{-1}$)	dh_θ/dH_θ	dh_A/dt ($Mx^2\ s^{-1}$)	dh_A/dH_A
LMSAL	4194	−3.23E+37	2.21E+36	−0.07	−3.59E+36	0.11
FLCT	4195	−3.23E+37	2.24E+36	−0.07	−2.81E+36	0.09
DAVE	4169	−3.23E+37	3.21E+36	−0.10	−7.50E+36	0.23
IM	4195	−3.23E+37	−9.00E+36	0.28	−8.15E+36	0.25
ILCT	4195	−3.23E+37	−1.18E+37	0.37	−1.18E+37	0.36
MEF	3762	−3.21E+37[b]	−3.19E+37	1.00	−3.24E+37	0.99
MSR	4127	−3.23E+37	1.17E+37	−0.36	1.17E+37	−0.36

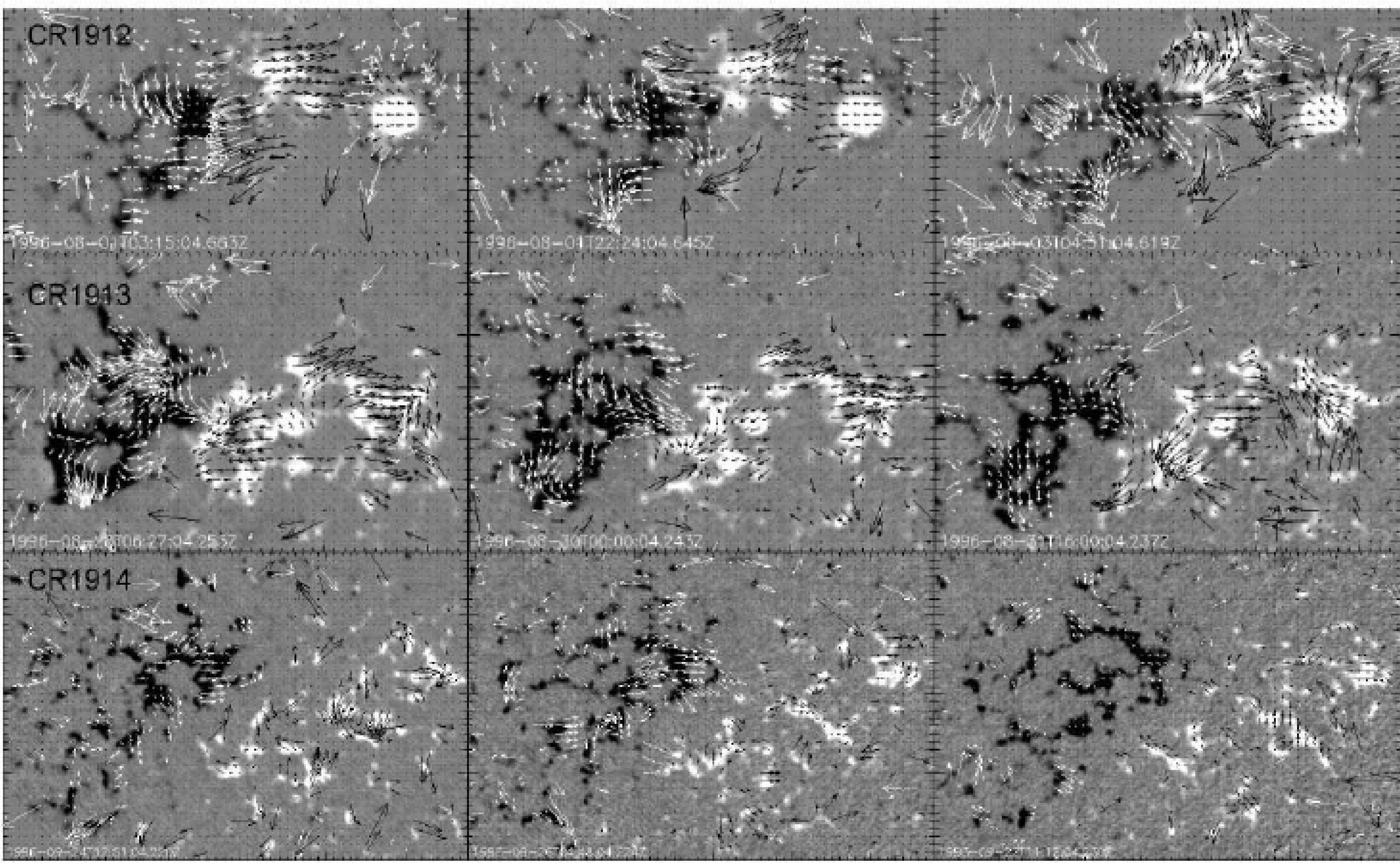
[a] Except where noted, $dH_A/dt = dH_\theta/dt$.
[b] Here $dH_A/dt = -3.24 \times 10^{37}$.

For a complete discussion of the velocity inversion validation effort, please see Welsch et al. 2007, ApJ 670, 1434.

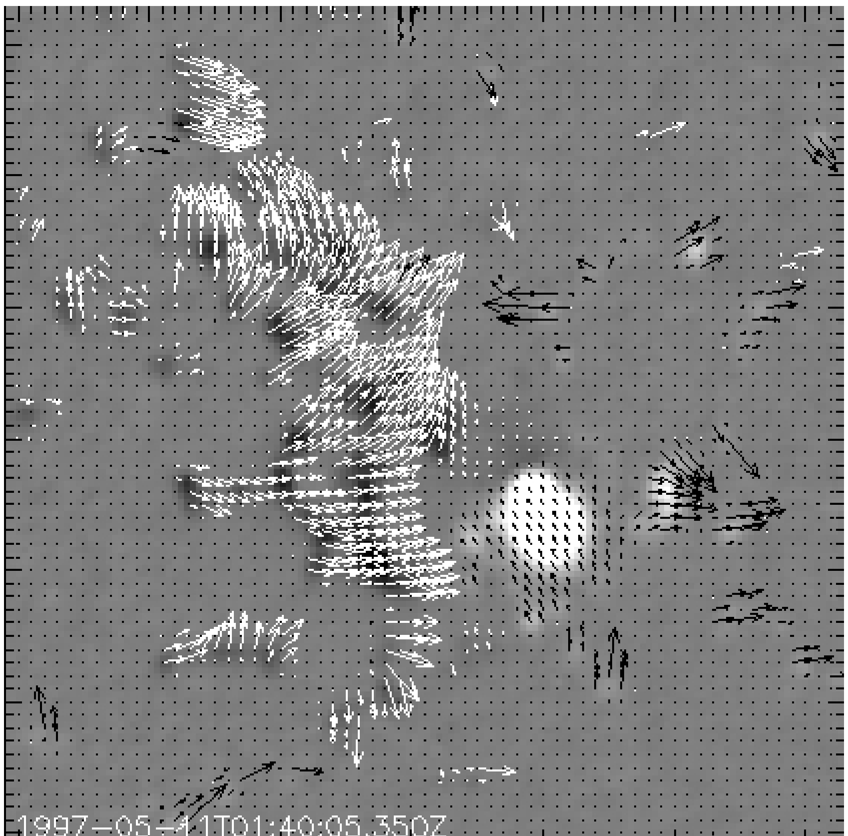
Can we use the velocity tools now in hand to improve predictions of solar flares or other space weather events?

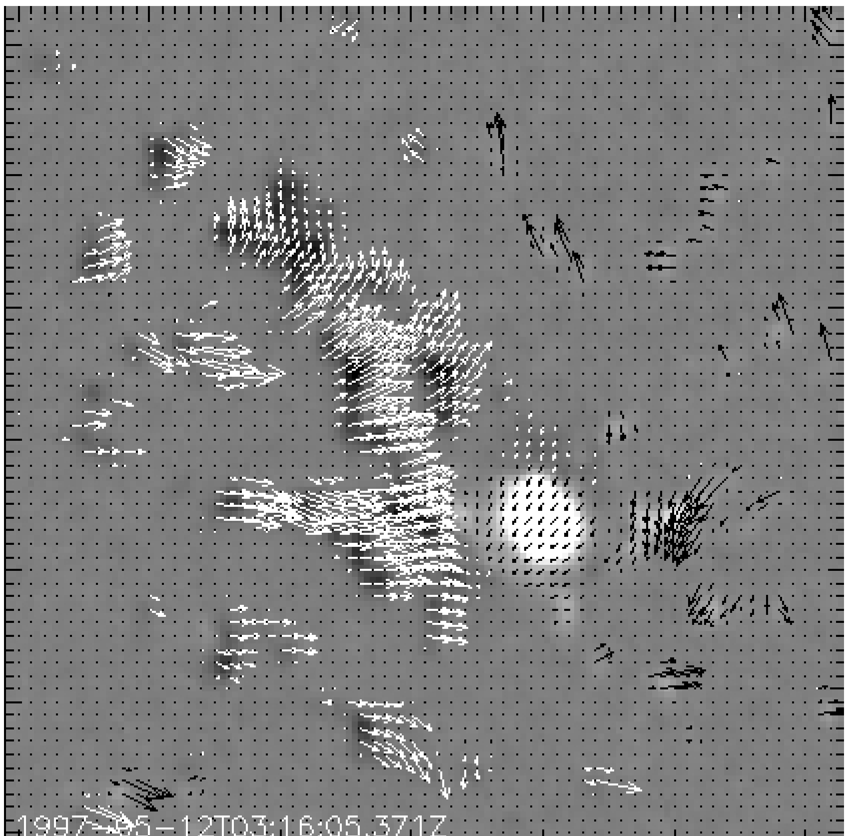
- Answer: We don’t know yet. Currently, determining flows in active regions in a regular, systematic way, and analyzing the results for a wide variety of different active regions has only recently been attempted (e.g. Li & Welsch, Muglach, work in progress).
- Because the fundamental physical arguments for the importance of flows are so strong, it is essential we make the effort to at least try.
- There is an increasing level of effort in the solar community in determining flows from line-of-sight and vector magnetograms, as illustrated in the number of researchers participating in the shootout exercise.
- Using observationally determined flow fields to determine boundary conditions for time-dependent MHD models of the solar atmosphere are currently under way (UCB/Abbett, Michigan, UAH)

LCT-determined flows in active-regions followed for several solar rotations



Flows in a well-studied active region that produced a flare and coronal mass ejection (AR 8038)





How much information about the magnetic induction equation can one extract from a time sequence of (error-free) vector magnetograms taken in a single layer?

$$\frac{\partial B_x}{\partial t} = c\left(\boxed{\frac{\partial E_y}{\partial z}} - \frac{\partial E_z}{\partial y}\right)$$

$$\frac{\partial B_y}{\partial t} = c\left(\frac{\partial E_z}{\partial x} - \boxed{\frac{\partial E_x}{\partial z}}\right)$$

$$\frac{\partial B_z}{\partial t} = c\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x}\right)$$

Kusano et al. (2002, ApJ 577, 501) stated that only the equation for the normal component of B (B_z) can be constrained by sequences of vector magnetograms, because measurements in a single layer contain no information about vertical derivatives. Nearly all current work on deriving flow fields or electric fields make this same assumption. **But is this statement true?**

The 3-D induction equation, using a poloidal-toroidal decomposition:

$$\dot{\mathbf{B}} = \nabla \times \nabla \times \dot{\beta}\hat{\mathbf{z}} + \nabla \times \dot{\mathcal{J}}\hat{\mathbf{z}} = -c\nabla \times \mathbf{E}$$

The vector magnetogram data time sequence can be related to the following 3 two-dimensional Poisson equations, by differencing in time:

$$\nabla_h^2 \dot{\beta} = -\dot{\mathrm{B}}_z \quad ;$$

$$\nabla_h^2 \dot{\mathcal{J}} = -\frac{4\pi \dot{J}_z}{c} = -\hat{\mathbf{z}} \cdot (\nabla_h \times \dot{\mathbf{B}}_h) \quad ;$$

$$\nabla_h^2 \left(\frac{\partial \dot{\beta}}{\partial z} \right) = \nabla_h \cdot \dot{\mathbf{B}}_h$$

Since the time derivative of the magnetic field is equal to -c∇xE, we can immediately relate the curl of E and E itself to the potential functions determined from the 3 Poisson equations:

$$\nabla \times \mathbf{E} = \frac{-1}{c} \nabla_h \left(\frac{\partial \dot{\beta}}{\partial z} \right) - \frac{1}{c} \nabla_h \times \dot{\mathcal{J}}\,\hat{\mathbf{z}} + \frac{1}{c} \nabla_h^2 \dot{\beta}\hat{\mathbf{z}}$$

$$\mathbf{E} = \frac{-1}{c} \left(\nabla_h \times \dot{\beta}\,\hat{\mathbf{z}} + \dot{\mathcal{J}}\,\hat{\mathbf{z}} \right) - \nabla \psi = \mathbf{E}_I - \nabla \psi$$

Note the appearance of the 3-d gradient of an unspecified scalar potential ψ.

Relating ∇xE and E to the 3 potential functions:

The induction equation can be written in component form to illustrate precisely where the depth derivative terms $\partial E_y/\partial z$ and $\partial E_x/\partial z$ occur:

$$\frac{\partial B_x}{\partial t} = c\left(\boxed{\frac{\partial E_y}{\partial z}} - \frac{\partial E_z}{\partial y}\right) = \boxed{\frac{\partial}{\partial x}\frac{\partial \dot{\beta}}{\partial z}} + \frac{\partial \dot{\mathcal{J}}}{\partial y}$$

$$\frac{\partial B_y}{\partial t} = c\left(\frac{\partial E_z}{\partial x} \boxed{- \frac{\partial E_x}{\partial z}}\right) = \boxed{\frac{\partial}{\partial y}\frac{\partial \dot{\beta}}{\partial z}} - \frac{\partial \dot{\mathcal{J}}}{\partial x}$$

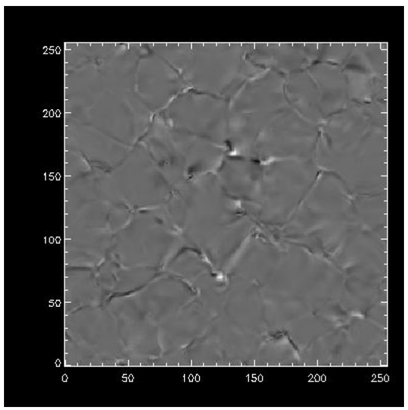
$$\frac{\partial B_z}{\partial t} = c\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x}\right) = -\nabla_h^2 \dot{\beta}.$$

Note that these terms originate from the horizontal divergence of time derivatives of the horizontal field.

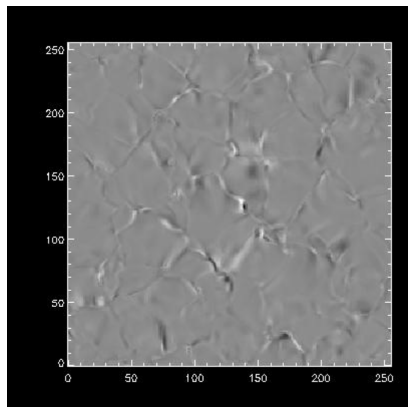
Does it work?

First test: From $\partial B_x/\partial t$, $\partial B_y/\partial t$,$\partial B_z/\partial t$ computed from Bill's RADMHD simulation of the Quiet Sun, solve the 3 Poisson equations with boundary conditions as described, and then go back and calculate $\partial \mathbf{B}/\partial t$ from slide (14) and see how well they agree.

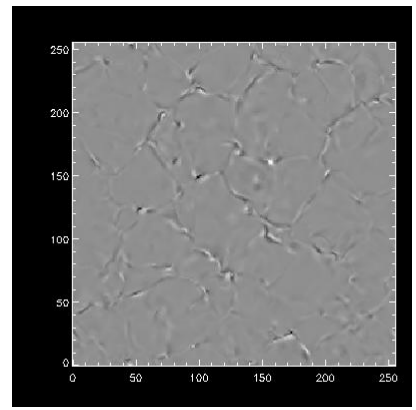
$\partial B_x/\partial t$ RADMHD



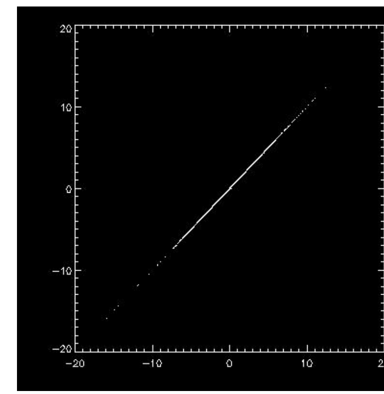
$\partial B_y/\partial t$ RADMHD



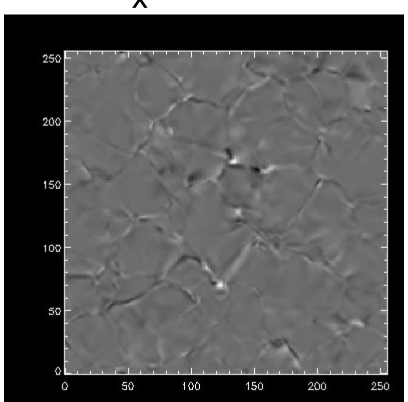
$\partial B_z/\partial t$ RADMHD



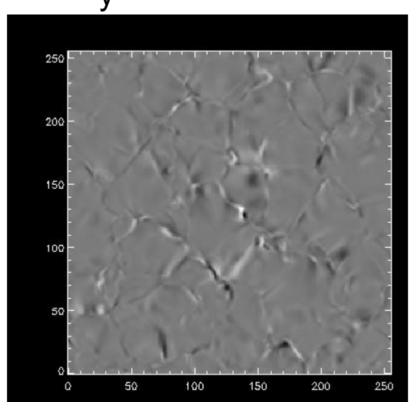
$\partial B_z/\partial t$ vs $\partial B_z/\partial t$



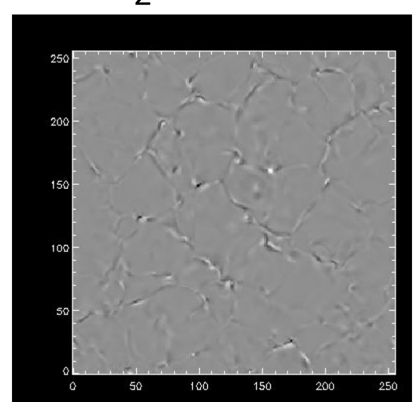
$\partial B_x/\partial t$ derived



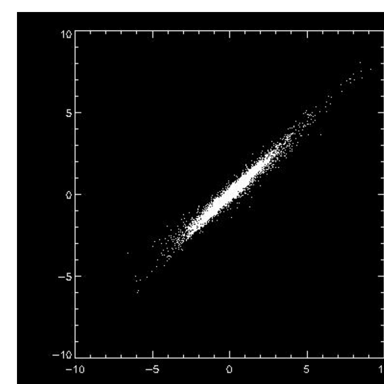
$\partial B_y/\partial t$ derived



$\partial B_z/\partial t$ derived

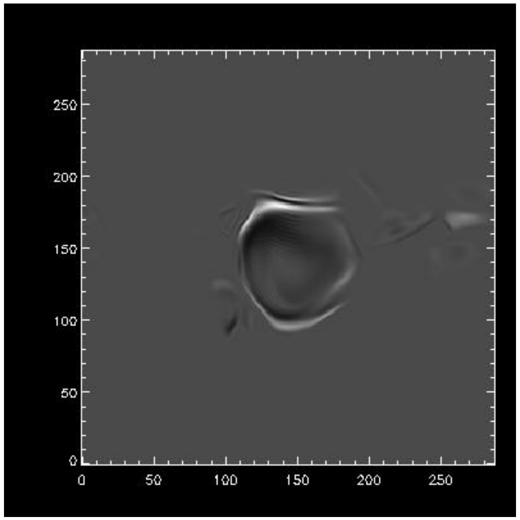


$\partial B_x/\partial t$ vs $\partial B_x/\partial t$

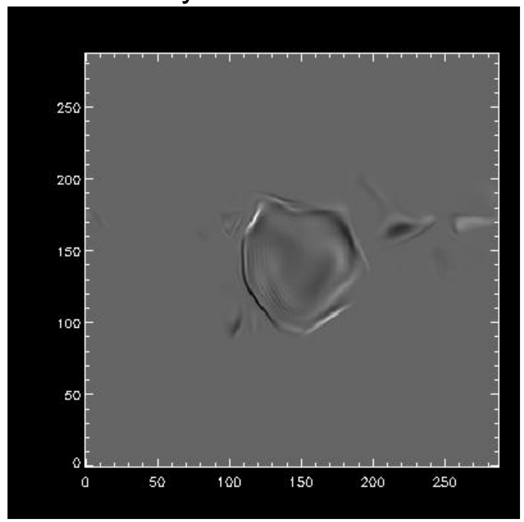


Comparison to velocity shootout case:

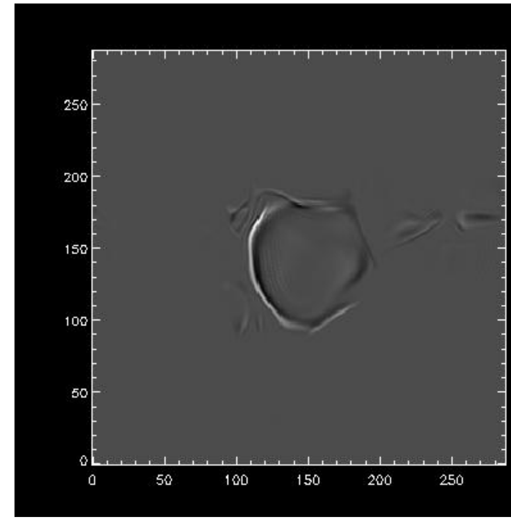
$\partial B_x/\partial t$ ANMHD



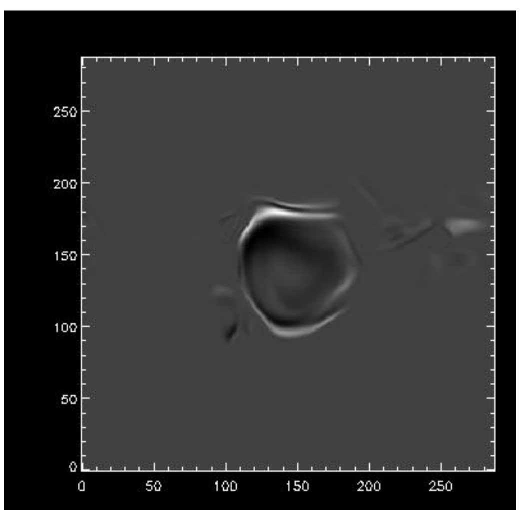
$\partial B_y/\partial t$ ANMHD



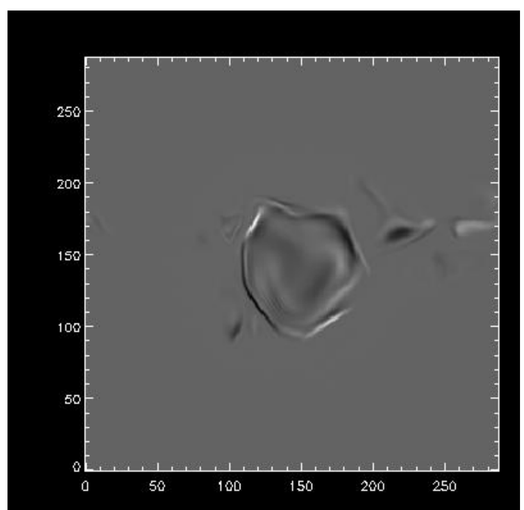
$\partial B_z/\partial t$ ANMHD



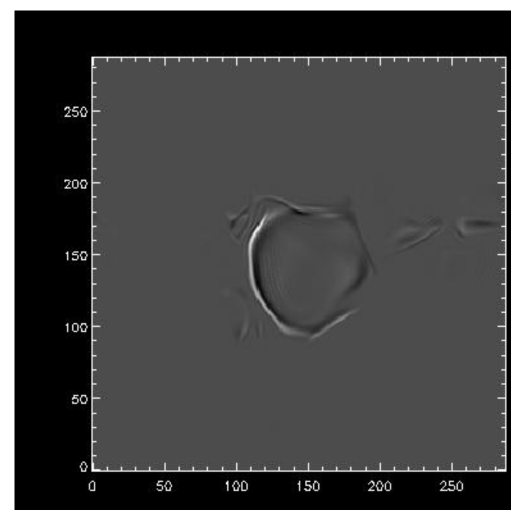
$\partial B_x/\partial t$ derived



$\partial B_y/\partial t$ derived

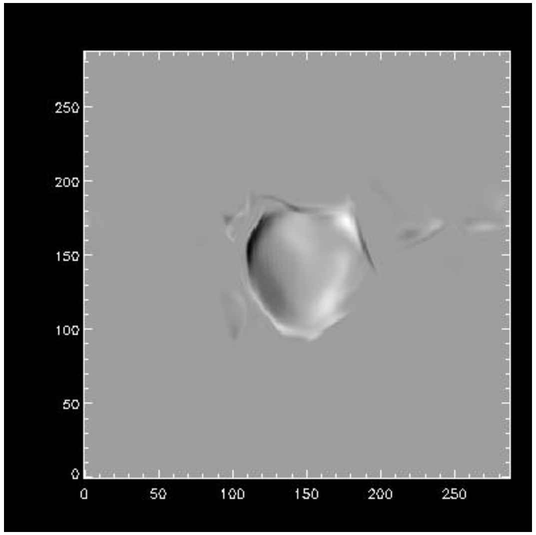


$\partial B_z/\partial t$ derived

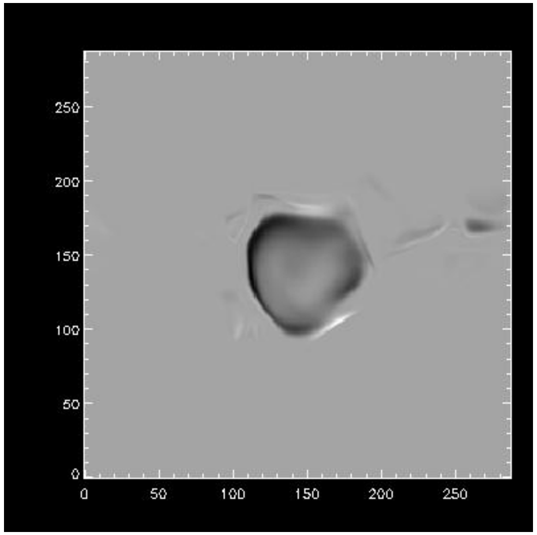


Velocity shoot out case (cont'd)

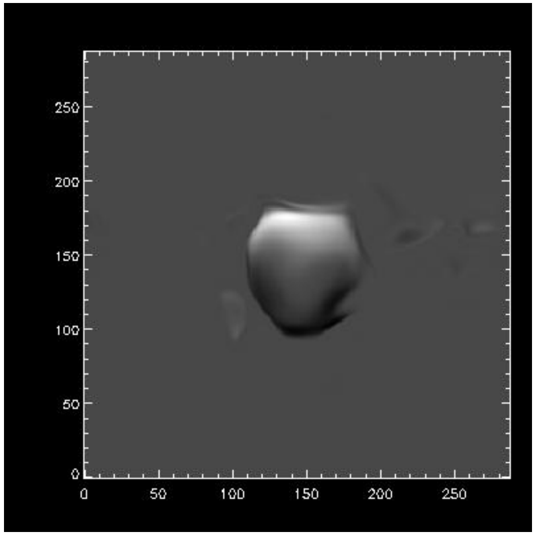
E_x



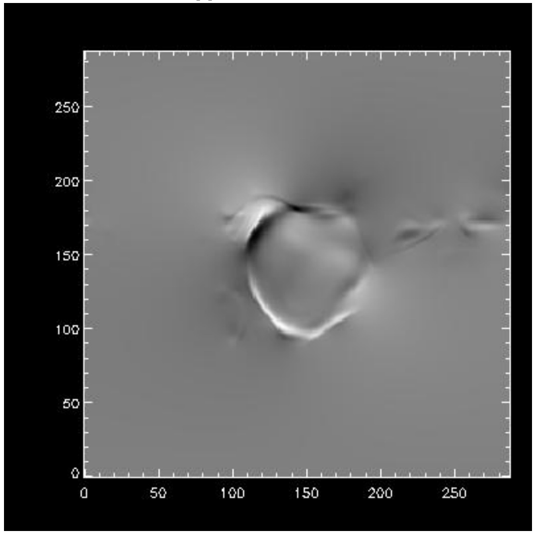
E_y



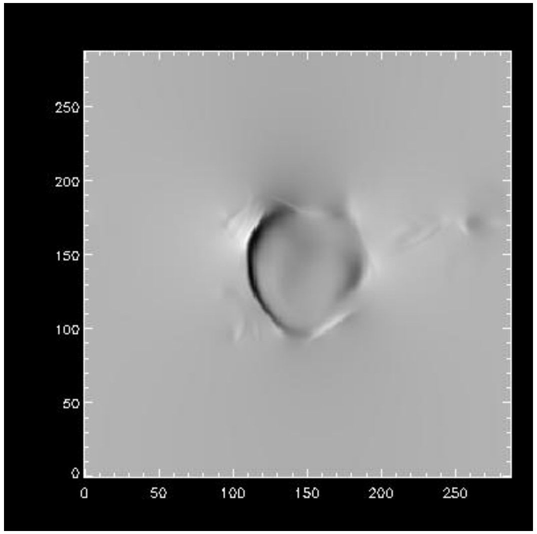
E_z



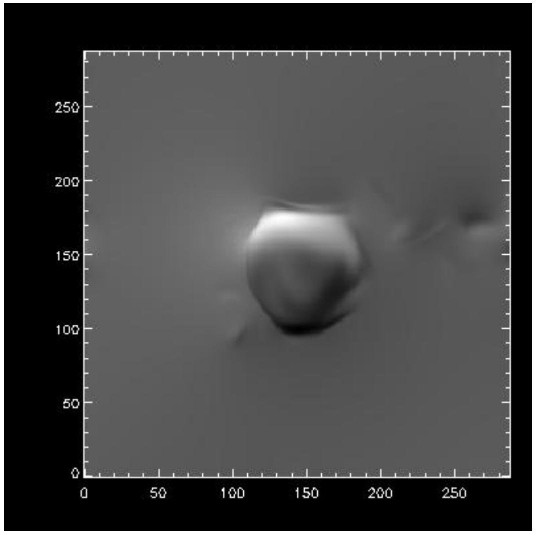
E_x derived



E_y derived



E_z derived



Summary of 3-D Electric Field Inversion

Given the knowledge of the magnetic field vector and its time derivative at a single time, in a closed 2-d region, we can derive an electric field whose curl will provide the observed time derivative of **B**.

However, the electric field thus derived is not uniquely specified. The gradient of a scalar potential can be added to the electric field without affecting its curl or the time evolution of **B**.

Additional physical constraints on the electric field can be given by specifying an equation that the scalar potential must obey.

Status of using flows and electric fields to improve forecasts of flares, CMEs, and other events:

- There has been an explosion of new interest in determining flows and electric fields from line-of-sight and vector magnetograms
- Validation exercises for different techniques has started
- Flows are currently being used in research projects to determine signatures of pre-flare/CME energy buildup
- To evaluate the usefulness of flows/electric fields for solar event prediction, the flows of many more active regions need to be determined and analyzed
- There is hope of being able to use all 3 components of the magnetic induction equation to determine flows and electric fields.