Analysis and Visualization of Small-Scale Structures Occurring in High-Resolution MHD Simulations

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Overview: A new interactive analysis and visualization tool suite ("VAPOR") has been applied to the results of an MHD simulation on a grid of 1536^3 points. Using VAPOR, simulation data on very large grids can be analyzed and visualized directly from a wavelet representation, enabling interactive 3-D browsing of massive time-varying datasets. These techniques enabled the discovery of parallel current and vorticity sheets, that were found to fold or roll-up after an initial exponential phase. A self-similar evolution of the current and vorticity maxima was also identified and characterized using these methods.

Methodology: The recent advance in supercomputing performance is outstripping our ability to analyze and visualize simulation results. VAPOR is a desktop application customized to the need of the turbulence community to understand these massive time-varying datasets. VAPOR's development is guided by a steering committee of earth science fluid flow researchers. Major features include:

- Use of a multiscale data representation, enabling immediate access to time-varying volume data. Massive datasets can be examined at low resolution, or one can zoom into the data for high resolution images of regions of interest.

- Users perform analysis on regions of interest using an analysis package such as IDL®, and can immediately visualize the results alongside user data.

- Support for interactive volume rendering, steady and unsteady flow integration, contour planes, and data probing.

- User interface customized to the usability requirements of turbulence researchers.

Analysis and discovery process. The data can be interactively visualized and analyzed by identifying regions of interest from low-resolution images, then performing high-resolution rendering and analysis on those regions. With this MHD dataset, the magnitude of the current is first visualized at lowered resolution (192^3). Regions of highest current intensity are identified with increased opacity. These regions are likely sites for current sheets to develop.

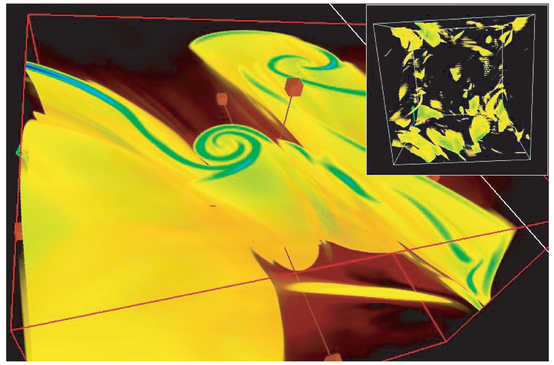

Fig 1: Beginning with a rendering of the full current magnitude at low resolution (inset), a region of interest is identified and magnified, resulting in a high resolution image of the current magnitude in the region of interest. This volume rendering shows the formation of intertwined current sheets, i.e. a "current roll".

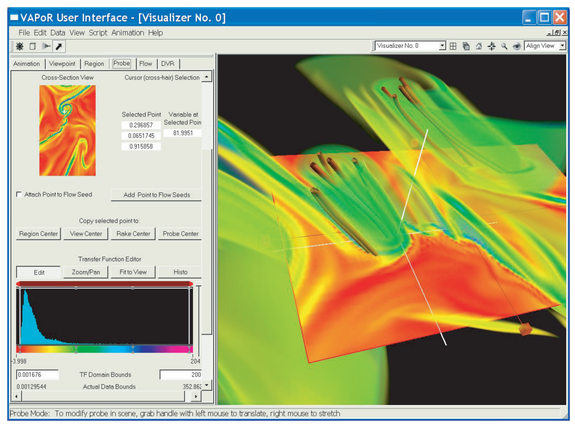

Fig 2: The data probe is then used to position flow seeds at positions of maximal current intensity. Magnetic field lines are constructed by integrating the magnetic field at full resolution in the region of interest. These field lines are seen to follow the axis of the current roll.

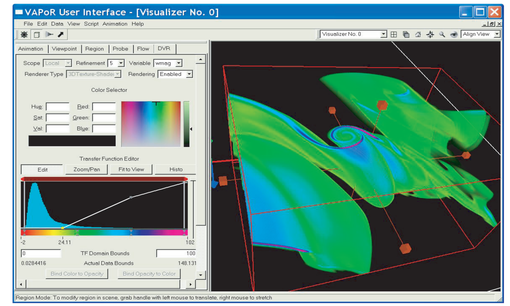

Fig 3: The vorticity field is immediately calculated in the region of interest, by applying an IDL routine to the region identified from the visualization. The vorticity is then visualized with a transfer function that associates increased opacity with larger enstrophy. Largest enstrophy is seen to coincide with the current roll.

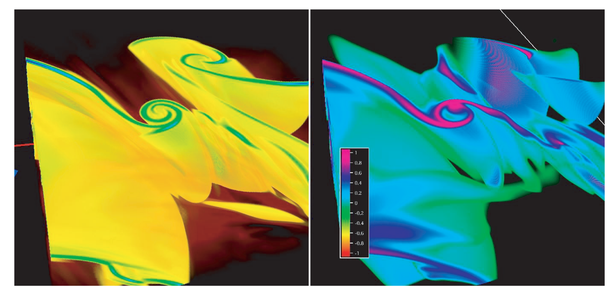

Fig 4: The volume rendering on the right illustrates maximal Alfvenization (correlation between **v** and **b**). Increased opacity and red-violet color (calibrated in color scale) distinguish highest correlation. Side-by-side comparison with the current roll (left) shows stronger correlation nearest the current roll.

Simulation: For the analysis and visualization, we use data from a three-dimensional simulation of the MHD equations in a periodic box using 1536^3 grid points. The code solves the incompressible MHD equations (in dimensionless Alfvénic units),

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v} = -\frac{1}{\rho_0}\nabla\mathcal{P} + \mathbf{j}\times\mathbf{b} + \nu\nabla^2\mathbf{v}$$

$$\frac{\partial \mathbf{b}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{b}) + \eta\nabla^2\mathbf{b}$$

using a pseudospectral method in space and Runge-Kutta to evolve in time. Here, **v** is the velocity field, **b** is the magnetic induction, **j** is the current density, P is the pressure, $\rho_0 = 1$ is the (constant) density, and $\nu = \eta = 2\times10^{-4}$ are respectively the kinematic viscosity and the magnetic diffusivity. Both **v** and **b** are divergence-free.

The initial conditions are given by a superposition of Beltrami (helical) flows for $k = 1,2$, and 3, and random fluctuations in the small scales ($k>3$). The initial velocity and magnetic field spectra are taken ~ $k^{-3}\exp[-2(k/k_0)^2]$. Initially, the magnetic and kinetic energies are $E_V = E_M = 0.5$, the cross helicity $H_C \sim 10^{-4}$, and the magnetic helicity $H_M \sim 0.45$.

Physics: As the system evolves from the smooth initial conditions, current sheets are formed. The initial growth of the current density **j** in these structures is exponential, as expected from a linear instability analysis. As the non-linear terms in the MHD equations get larger, a self-similar regime begins in which the current sheets get thinner and the current density grows in each structure as t^3. Finally, Kelvin-Helmoltz instabilities with rolling up of such sheets are observed (Fig. 1).

In these structures, magnetic field lines are parallel to the roll, in such a way that magnetic tension does not prevent the occurrence of the instability (Fig 2). Vortex sheets are collocated with the current sheets (Fig. 3). Alfvenization of the flow (**v** ~ ± **b**) is rather strong in the vicinity of the sheets, although globally the flow remains uncorrelated (Fig. 4). This local Alfvenization gives stability to such structures.

References: P.D. Mininni, A. Pouquet, and D.C. Montgomery, "Small-scale structures in three-dimensional magnetohydrodynamic turbulence", *Phys. Rev. Lett.* (in press); arXiv:physics/0607269.

VAPOR website, including documentation and software downloads, is at: http://www.vapor.ucar.edu .

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