Magnetospheric Visualization

How to Extract Global Measurements for End Users

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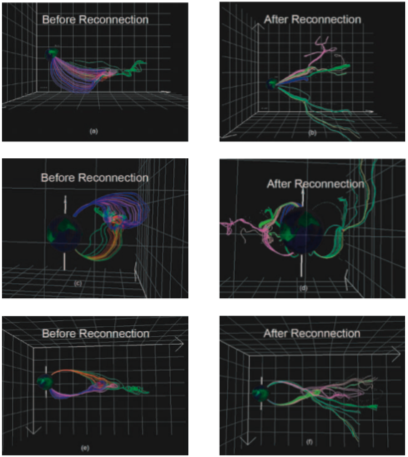
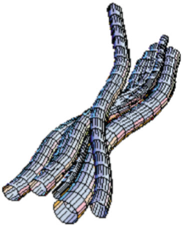
*See graphics literature for a similar approach to analysis for fluid flows [1].

Examples from the Space Physics Community



D. Cai *et al.*, 2007



Consolini *et al.*, 2002

Problems with standard tools

- 2D Cross sections of scalars, including isocontours
- 3D field line traces through vector fields
- 3D isosurfaces (e.g. pressure, density)
- Artists' interpretations of the underlying structure

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- Useful, but difficult to interpret. Fundamentally local.
- Far removed from simulation...

Existing Visualization techniques tend to *hide* the information scientists are interested in!

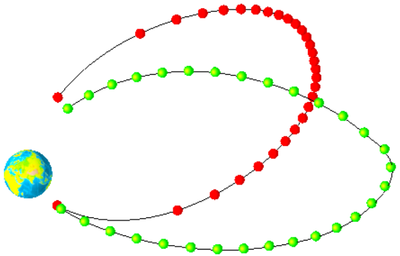
Open Questions

How do we reduce the simulations in a way that provides clear physical insight to users?

To Magnetospheric physicists, this means...

- How do we illustrate magnetic field geometry apart from field line depiction?
- How to tie field line geometry to global metrics?
- How do we avoid the overhead of redundancy in global field line traces?
- How do we interpret the mapping of ionospheric quantities, such as Field-Aligned Currents (FACs)?

Start Simple: Field line interpolation (1-D)



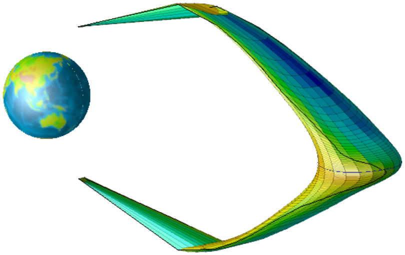
Field lines with resolution lowered to just 30 vertices each. Basic shape can still be captured.

Reduce the resolution of each field line.

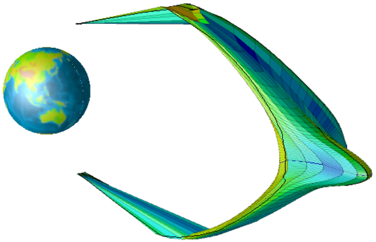
- Given $\vec{F}(\vec{r})$, can parameterize by fixed partially integrated $\int ds/F$.
- Drastically reduces storage requirements for each trace.
- Weighting schemes are flexible: Figure shows partial flux tube volume (red) and field line length to parameterize two different field lines.

Permits... Flux Tube Construction (2-D)

Using the previous result, we can build surfaces by tracing from a given curve's vertices.

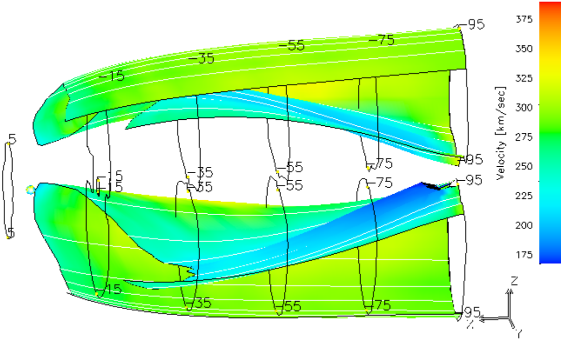


Flux tube mapped from a $1R_e$ ring of points in the equator (LFM)



The same flux tube, from a streakline trace after 8 minutes.

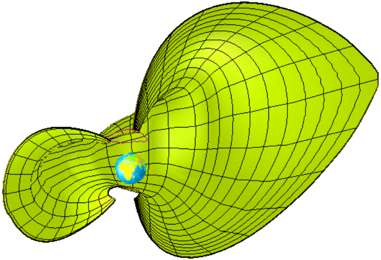
... Flow Surface Construction (2-D)



Plasma mantle drift surface, mapped backward in time from a $\beta = 1$ curve, $-95 R_E$ in the tail.

The Field Line Volume (3-D): Mapping Electric Potential

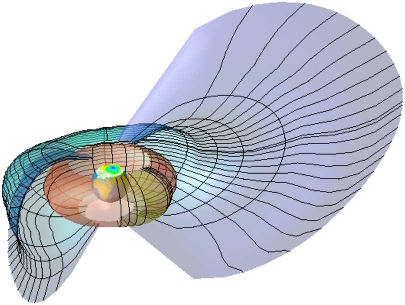
Volume elements can be built directly from surface connections.



LFM equipotential surface, created from field lines mapped from ionospheric surface elements.

- Yields a volumetric map of any quantity known at the surface.
- Previous Surfaces are now implicit - can be computed from isosurfaces.
- Implicit surface parameterizations (black curves).

The Field Line Volume (3-D): Drift Shell Construction



electron drift shells conserving energy invariant (assuming $\frac{\partial B}{\partial t} = 0$)

$$v_D = \frac{\vec{B}}{B^2} \times \nabla \left(\frac{\lambda V^{-2/3}}{q} + \Phi \right)$$

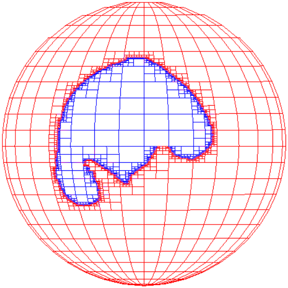
For energy invariant λ and flux tube volume $V = \int ds/B$

Average particle drift: along isosurfaces of an *effective* potential.

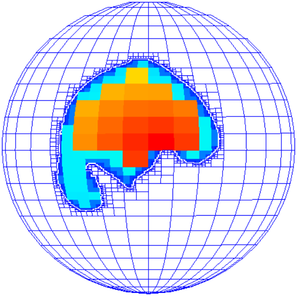
Drift shell visualization requires Φ and $V^{-2/3}$ everywhere.

3D Global Separatrix: Start with Local Topology Search

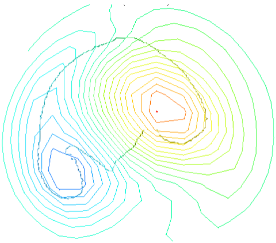
Multi-resolution Separatrix search inspired by Warren & Schaefer's scheme for subdivision surfaces [2]



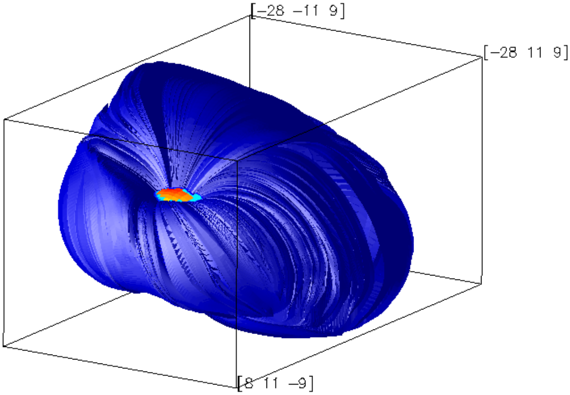
Fluxes computed per cell on the starting mesh



Reconnection potential can be calculated from $V_{max} - V_{min}$ along the separatrix



3D Global Separatrix: ... Build the Field Line Volume



3D separatrix surface, interpolated from 2602 field lines forming a volume. Compare with brute force volume search (61k).

Bounding box gives us a measure of both the geoeffective length and magnetopause location!

A framework for developing new metrics

A Suggested Workflow...

(1) Build a frame out of existing field line data (the bottleneck)

(2) Populate it with global physical measurements - your field integrations, topologies, ionospheric quantities, etc.

(3) Reparameterize to allow user definitions for regions of interest (ROI)

(4) Extract your characteristic measurement

(5) Apply to time series analysis if possible

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(5) Apply to time series analysis if possible
(6) Make bold statements about the physics captured by your code! (optional)

Defining your ROI

Choose wisely...

- use what you already know about your region of interest to guide your intuition! Ex: if entropy is conserved along along drift paths, what does that tell us about the motion of a constant entropy surface? How is the frozen-in condition *measured*?
- Build the ROI so that integrations are convenient: Boundary normals should point out of the ROI, and line integrals should be defined on the boundary surface and follow a right-hand rule (can choose field and surface normal).

Making your measurement

Could be the ROI's enclosed mass, volume, energy, or momentum.
Examples:

- the structure of FACs
- the volume of a flux tube volume
- the energy within a flux tube volume
- the total forces acting on a ROI and the relative forces
- the magnetic flux into the ROI ($\int E \cdot \vec{dl}$)
- the integrated vorticity of the flow ($\int V \cdot \vec{dl}$)

Tracking Measurement with Time

Suggestions & Words of warning

- Use streaklines or use quantities that we know are conserved with the flow.
- Be careful when applying the maxwell-faraday equation - it only works when the integration surface is tied to the flow!
- Exploit the divergence-less nature of your fields - can use half the integrated flux magnitude for closed surfaces, and use the zero-flux line for path integrations.

Implementation

- A set of macros/networks built in CISM-DX (Open-DX) with rapid prototyping.
- Project hosted on google code: `http://code.google.com/p/cismdxalgs/`
- Repository has video tutorials and a rough draft of a paper in progress. Comments/suggestions? apembroke@gmail.com
- AR Toolkit...

Delivery to the Community

There is a lot to do over the coming months...

- Integration with the CCMC framework will occur over the next year (starting now).
- Need to port methods into more stable working environments.
- Development of sanity checks are crucial: do ROI fluxes match volume integrals? Does the geometric volume match the volume within a flux tube?
- How do we adapt the approach to other Heliospheric regions?
- How do we convert global measurements into something relevant for spacecraft?
- The calculus of differential forms (DEC methods) inspired the approach - we should probably take geometry more seriously!

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You will see greater things than these!

Acknowledgements

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Acknowledgements

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- J. P. M. Hultquist, *Constructing stream surfaces in steady 3d vector fields*, VIS '92: Proceedings of the 3rd conference on Visualization '92 (Los Alamitos, CA, USA), IEEE Computer Society Press, 1992, pp. 171–178.
- Joe Warren and Scott Schaefer, *A factored approach to subdivision surfaces*, IEEE Comput. Graph. Appl. **24** (2004), no. 3, 74–81.