Space Hazards Induced near Earth by Large, Dynamic Storms (SHIELDS)

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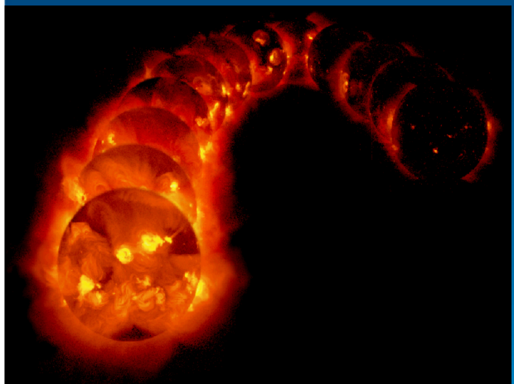
Los Alamos National Laboratory

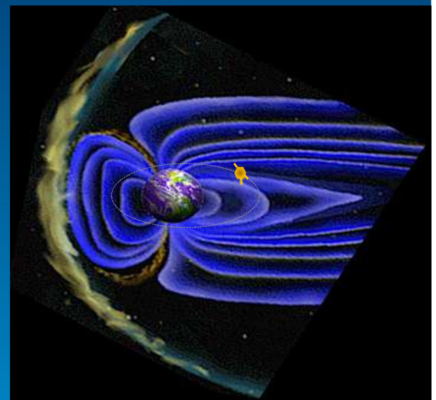
Project goals & impact:

- Develop a new modeling capability of the complex near-Earth environment for space assets protection

Science questions:



- What determines where and when hot plasma is injected into the inner magnetosphere?
- How are the injected particles transported, and how does the magnetosphere respond?
- What waves are excited and how do these waves feed back on the particle acceleration and loss?



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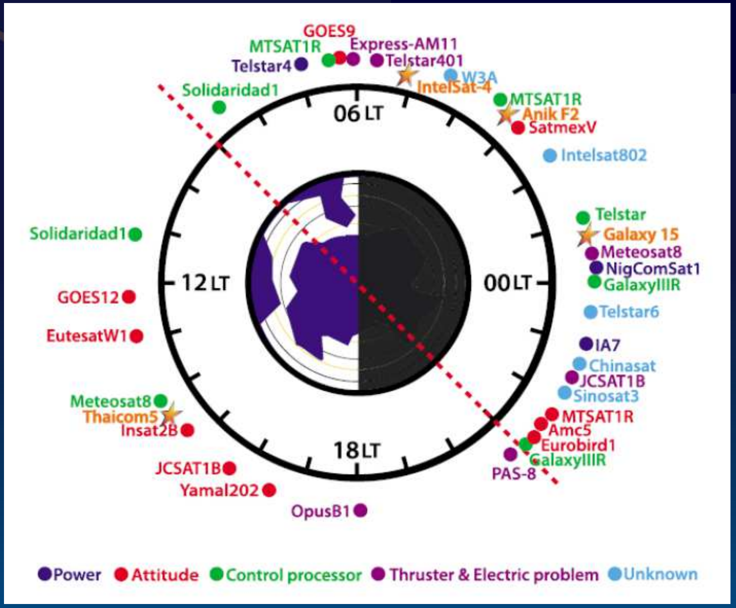
Satellite Anomaly Database

- GEO satellite anomalies occur mainly on the nightside, where the hot ~10's keV electron fluxes maximize

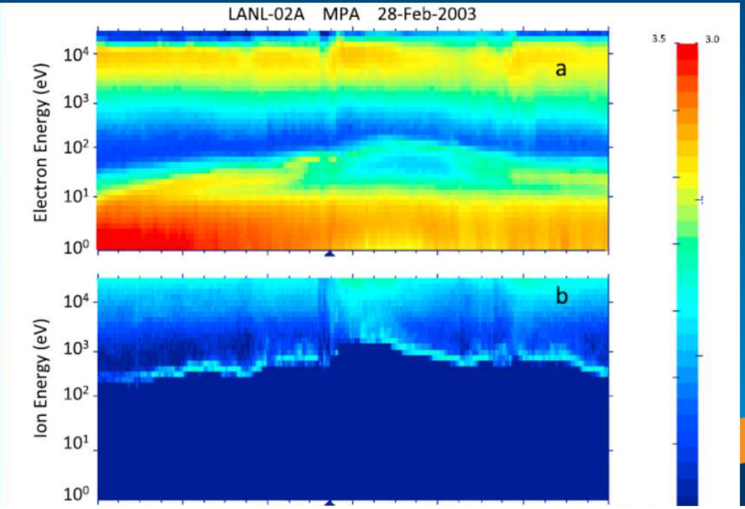
[Choi et al., 2011]



- LANL MPA data reveals the electron energy range (~5–10 keV) are most closely associated with satellite surface charging

- Enhanced surface charging probability exists (a) during higher values of Kp, (b) in the local time range from premidnight through dawn, (c) during equinox seasons, and (d) during the declining phase of the solar cycle

[Thomsen et al., 2013]



The accurate global specification of the surface charging environment (SCE) fluxes of hot (~10's keV) electrons is the gap that SHIELDS fills!

SHIELDS Team

Computer, Computational, and Statistical Sciences Division CCS

Theoretical Division

U. Michigan

Funded by the U. S. Department of Energy through the Los Alamos National Laboratory (LANL) Laboratory Directed Research and Development (LDRD) program, the SHIELDS framework is being developed by world-class experts in the fields of space sciences and computational plasma physics:

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- G. L. Delzanno (Co-PI), J. D. Moulton, H. Godinez, D. Svyatsky, T, LANL
- E. Lawrence, L. Vernon, CCS, LANL
- G. Tóth (Co-PI), D. Welling, Y. Chen, J. Haiducek, University of Michigan

Collaborators:

- M. Thomsen (PSI) and J. Birn, J. Borovsky and M. Denton, SSI
- J. Albert and S. Young, AFRL, Albuquerque, NM
- R. Horne, BAS, Cambridge, UK
- C. Lemon, The Aerospace Corporation, CA
- S. Markidis, I. B. Peng, KTH Stockholm, Sweden
- Y. Yu, Beihang University, Beijing, China

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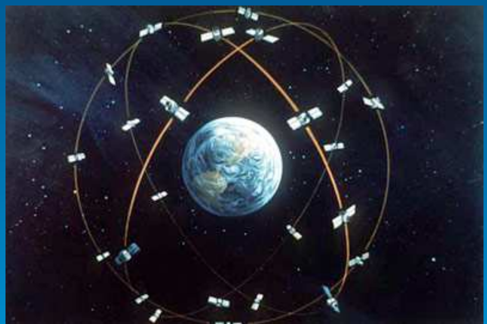
LDRD innovation for our nation

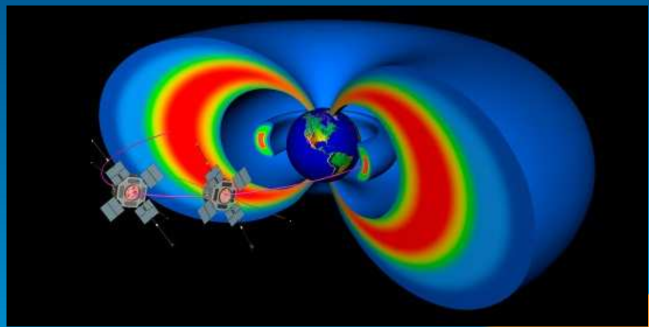
LANL Relevance

- The crucial national security need to maximize the safety of civilian and military satellites requires the ability to distinguish between various modes of failure
- Building on more than 50 years of space science heritage at the Laboratory
- Challenging problem ideally suited for LANL; the Laboratory has:
  - Unique scientific expertise in data analysis and physics-based modeling
  - Exceptional computational models and capabilities (RAM-SCB, PIC, substorm injection models) at the forefront of space plasma physics
  - Unique data to constrain and validate the models (GEO satellite data, RBSP)

Vela Satellite Program (1963-1984) for monitoring nuclear explosions



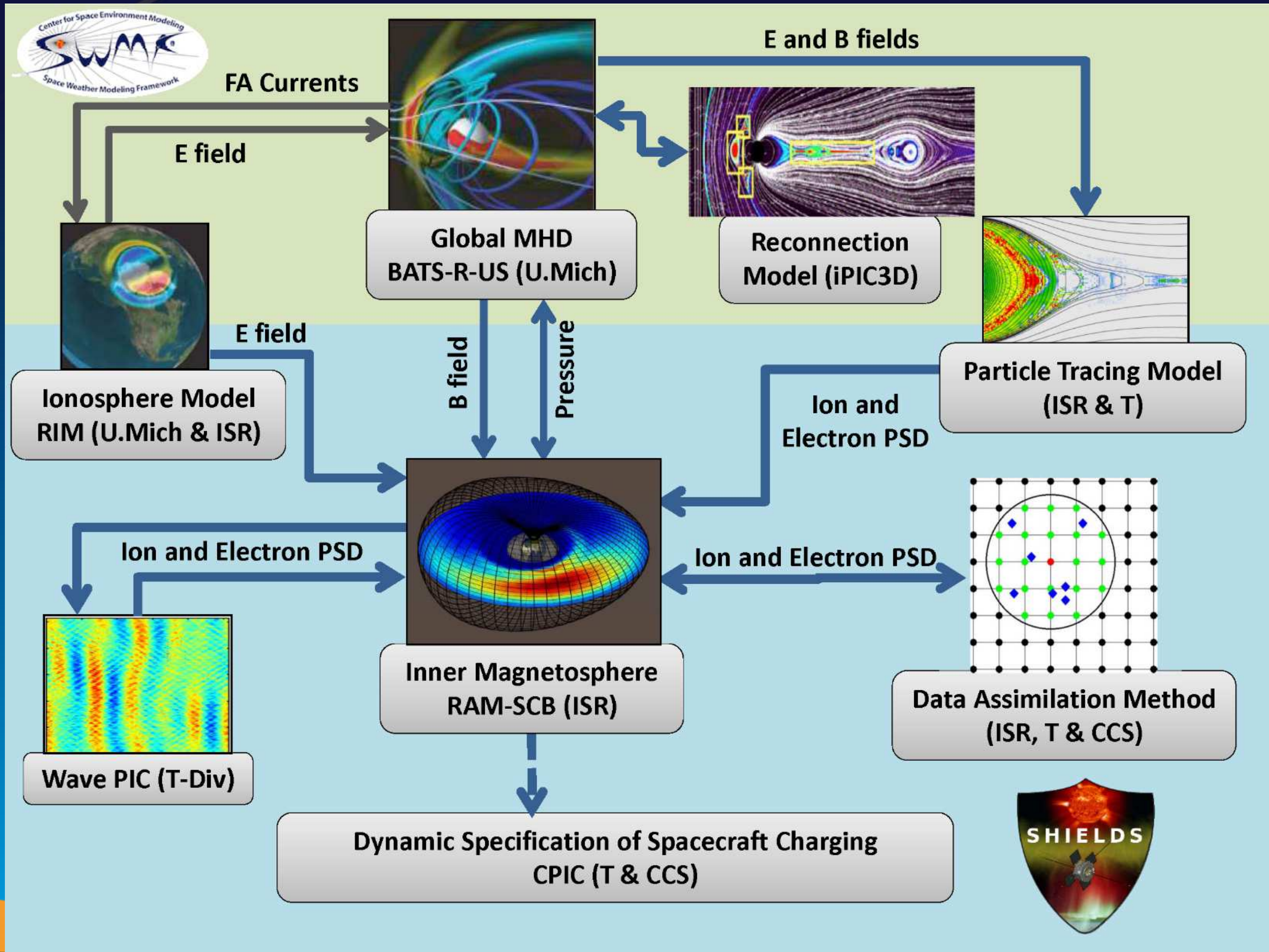
Global Positioning System (GPS) constellation (1978- to present), geosynchronous (GEO) satellites



Radiation Belt Storm Probes (RBSP) (2012-) exploring the extremes of space weather, now renamed as Van Allen Probes

The SHIELDS Framework

Bridging macro- and micro-scale models, combined with data assimilation tools:
- Capture rapid particle injection and acceleration during storms/substorms
- Include plasma wave generation and their feedback on the particles



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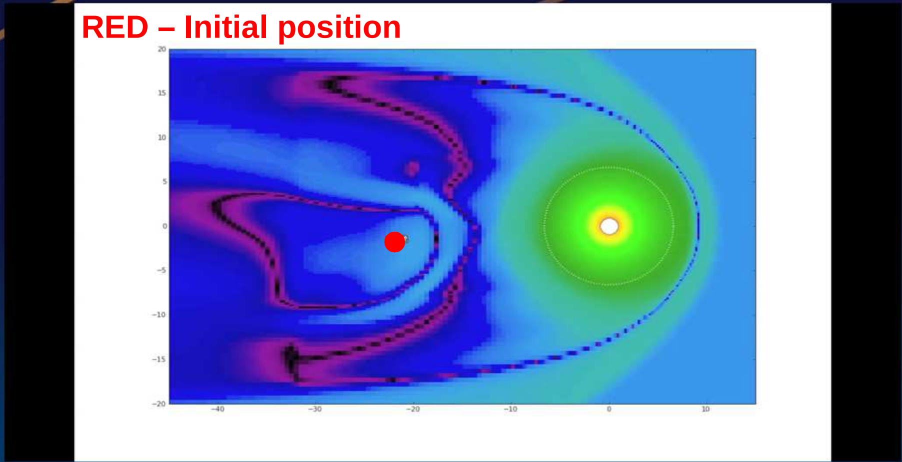
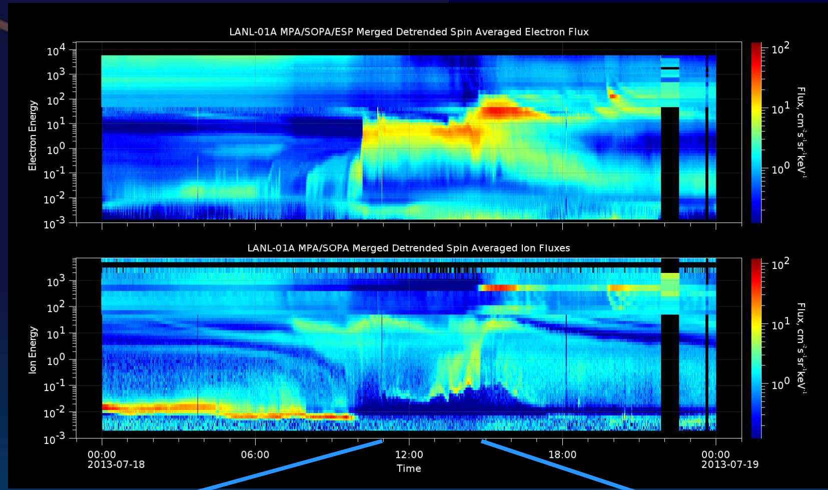
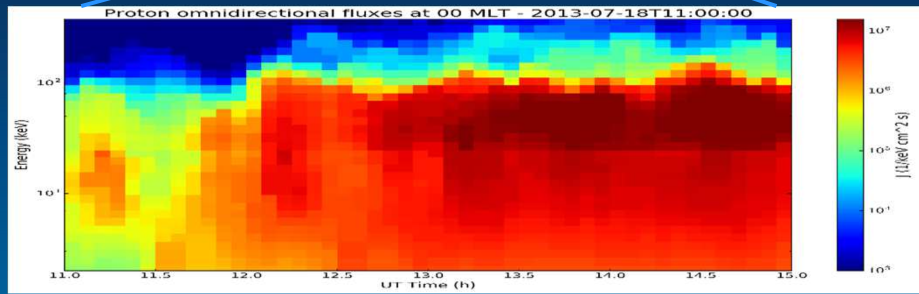
Strom/Substorm Dynamics



WHITE – Current position





- The Particle Tracing Model (PTM) was coupled with BATS-R-US
- Challenges that have been met:
  - interpolation across different levels of spatial resolution in BATS-R-US
  - Initial attempts using only MHD fields were not successful; coupling of inner magnetosphere via RAM-SCB is crucial for realistic results

- LANL spectrograms showing “perturbation-fluxes” (spectra are flattened to highlight energy dispersion features)
- Dispersionless electron injection at ~10UT; more complex ion injection activity between 13-15 UT
- The PTM qualitatively captures injection dynamics (note different scales)

POC: Mike Henderson, mghenderson@lanl.gov

3D MHD-EPIC Simulation of Earth's Dayside Reconnection

Physical parameters

- Ion inertial length scaling factor f =16
- Typical solar wind conditions:
  ρ= 5 amu/cm^3, U_X = -400km/s, B = [0,0,-5] nT

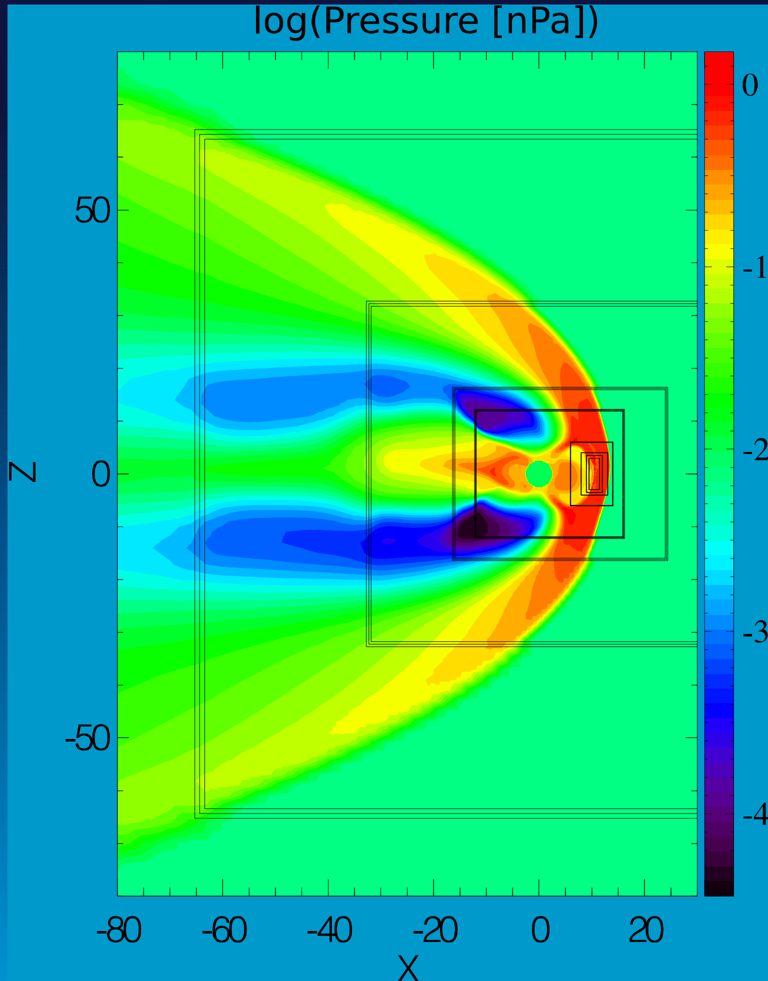
Hall MHD

- MHD domain: -224 < x < 32, -128 < y, z < 128Re
- At the magnetopause Δx=1/32Re (~200km)
- Hall MHD uses ~20% CPU time

PIC

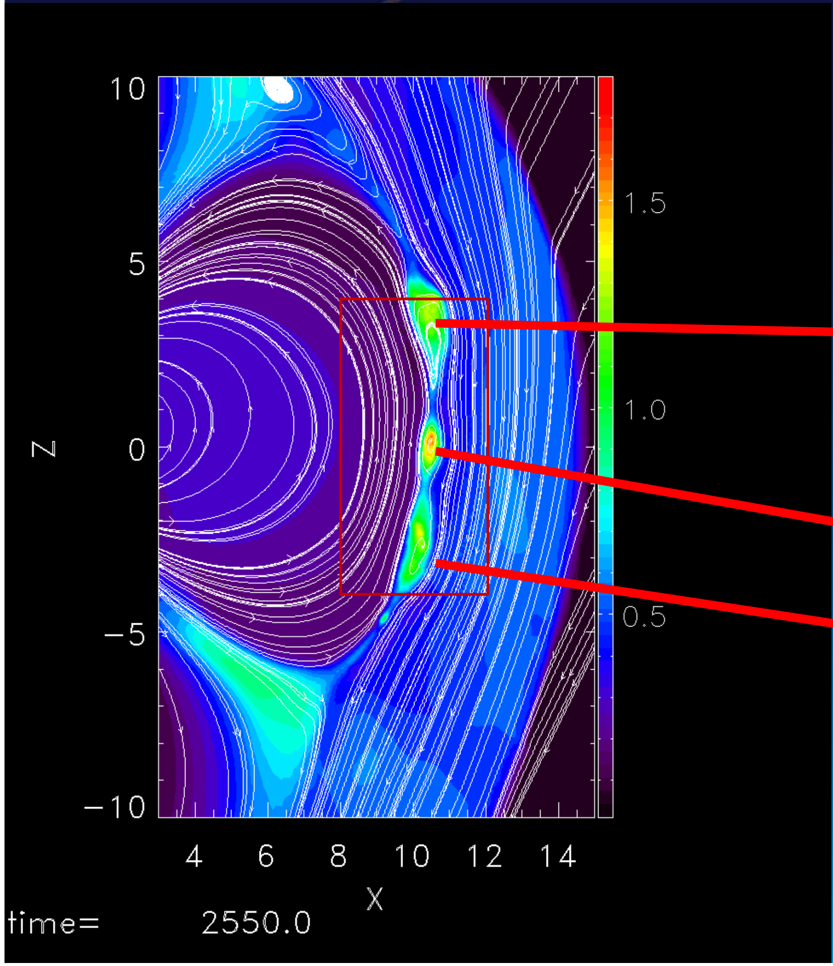
- PIC domain: 8 < x < 12, -6 < y < 6, -4 < z < 4Re
- Δx = 1/30Re: 5 cells per d_i (for f = 16)
- 216 particles per cell per species: 4.3B total
- Consuming ~80% simulation time

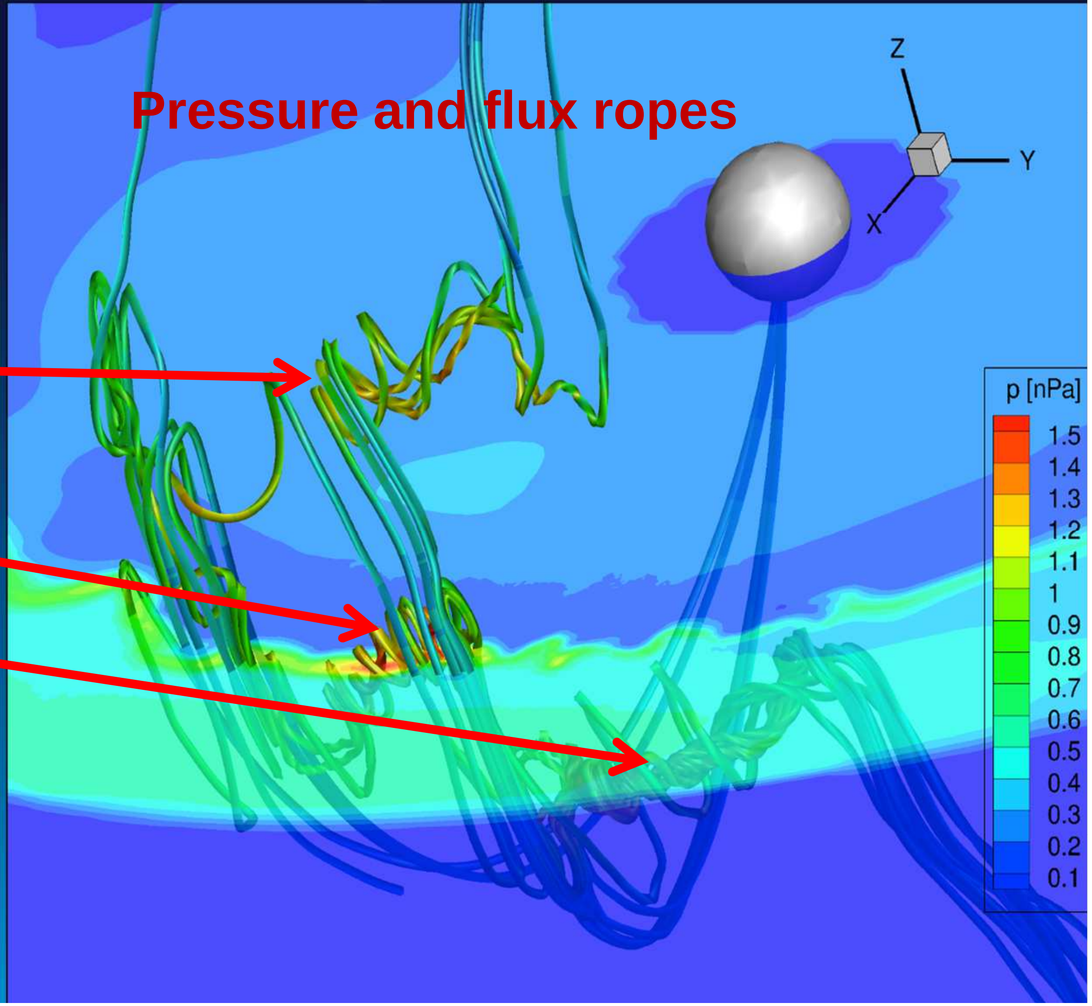
~2000 core hours modeling 1min



POC: Gabor Toth, gtoth@umich.edu

3D Structure of Flux Ropes at Earth Magnetopause





- Magnetic reconnection happens inside the PIC region & generates flux transfer events (FTEs)
- Shows that MHD-EPIC is the most efficient approach to kinetic modeling in a global system

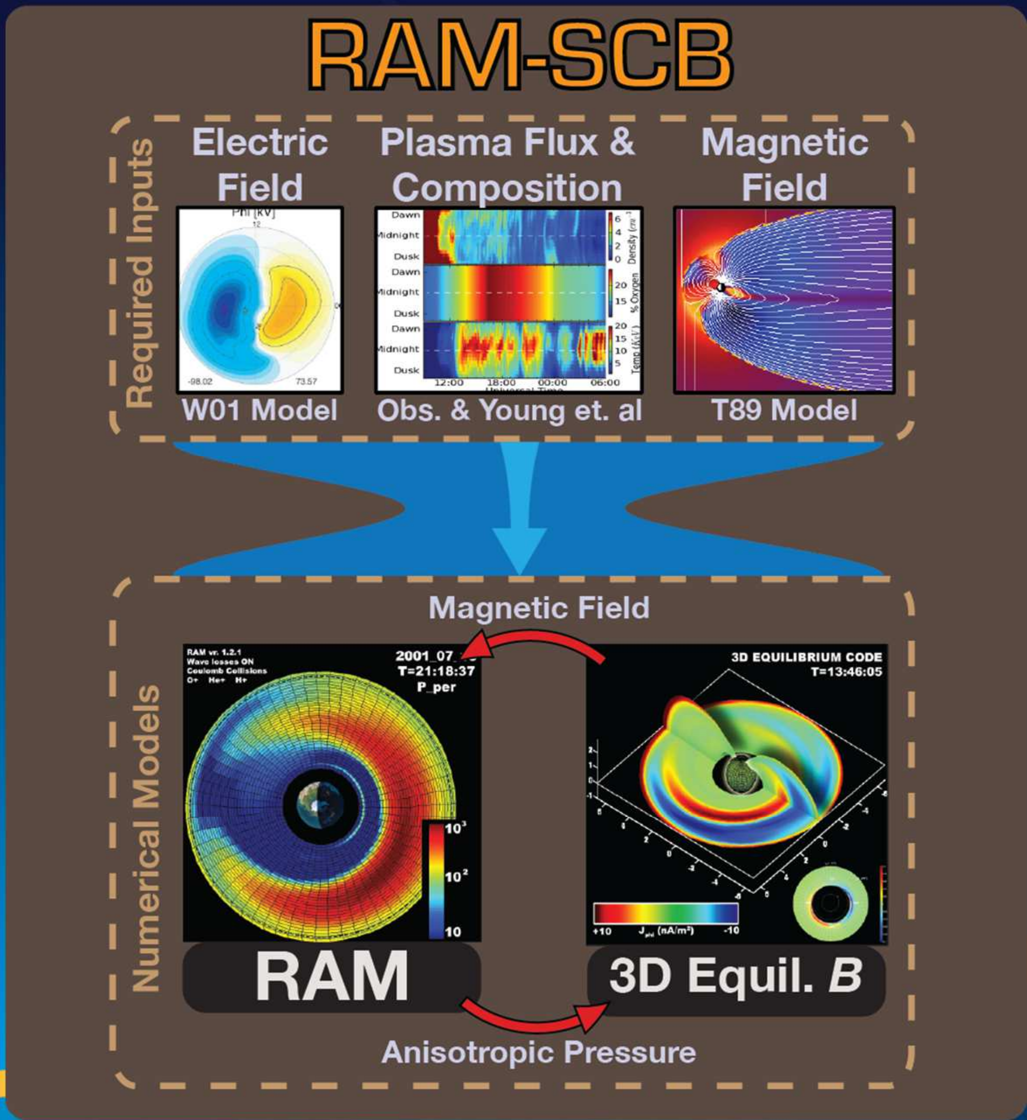
RAM-SCB

Ring current - Atmosphere interactions Model with Self-Consistent magnetic (B) field

- Ring current-atmosphere interactions model (RAM) [Jordanova et al., 1994, 2006; 2012]
  - Kinetic equation for H^+, O^+, and He^+ ions and electrons
  - Including all major loss processes
  - Convection and corotation E field
  - Updated to general B field
- 3D equilibrium code [Cheng, 1995; Zaharia et al., 2004; 2010]
  - Force-balanced equation

    $$\mathbf{J}\times\mathbf{B} - \nabla\cdot\mathbf{P} = 0$$

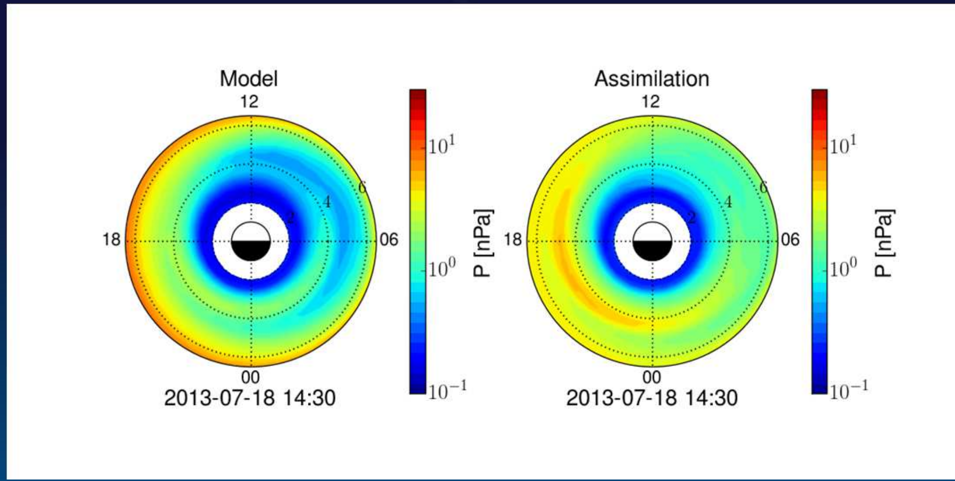
  - Euler potentials (flux coordinates)
  - Open source & available at: https://github.com/lanl/ram-scb



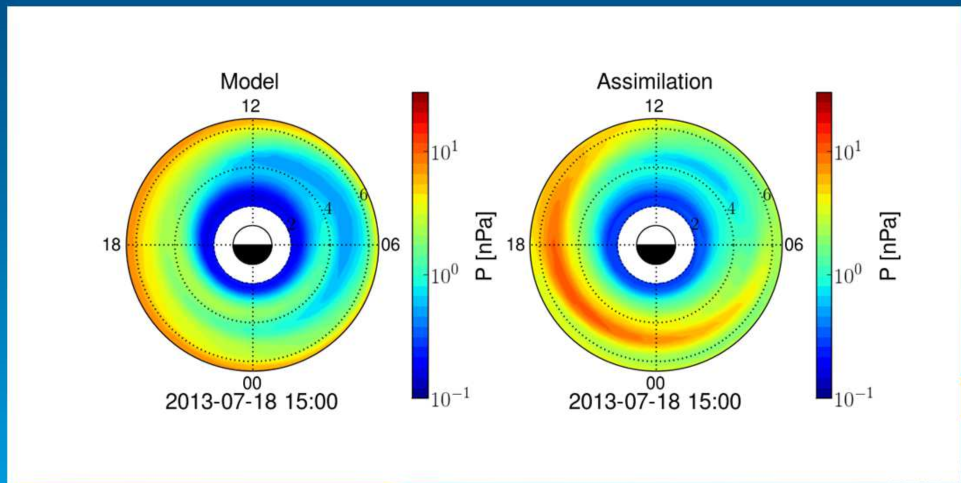
Data Assimilation

- Data assimilation fuse observations and model
- Assimilate VA Probe-B data into RAM-SCB, validate with VA Probe-A
- Use Singular Valued Decomposition (SVD) to define a new (better) basis for the state variables
- Significant enhancement is obtained compared to previous conventional method (LETKF)

Traditional LETKF method



New SVD based method

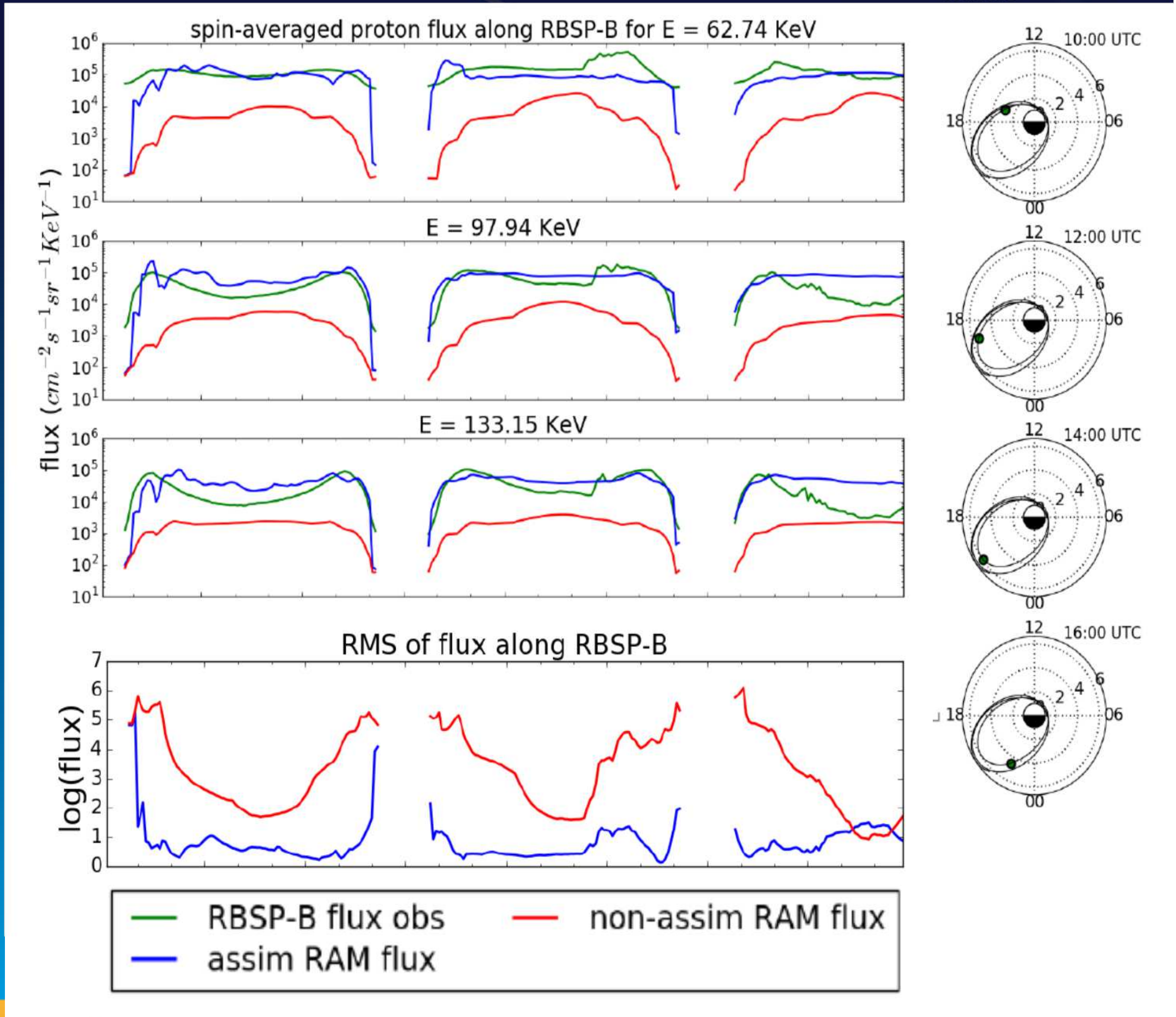


POC: Humberto Godinez, hgodinez@lanl.gov

Data Assimilation in RAM-SCB

- Assimilate VA Probe-A data into RAM-SCB, validate with VA Probe-B
- Results showed an order of magnitude improvement and significant error reduction

⇒ **First data assimilation for RAM-SCB completed, paper by Godinez et al. [2016] published in the *Geophys. Res. Letters***



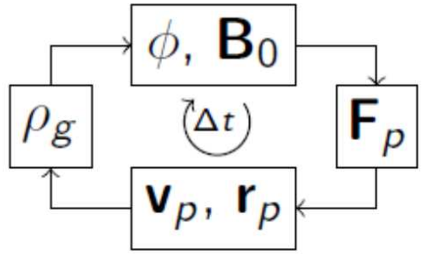
Curvilinear Particle-In-Cell (CPIC)

Los Alamos NATIONAL LABORATORY

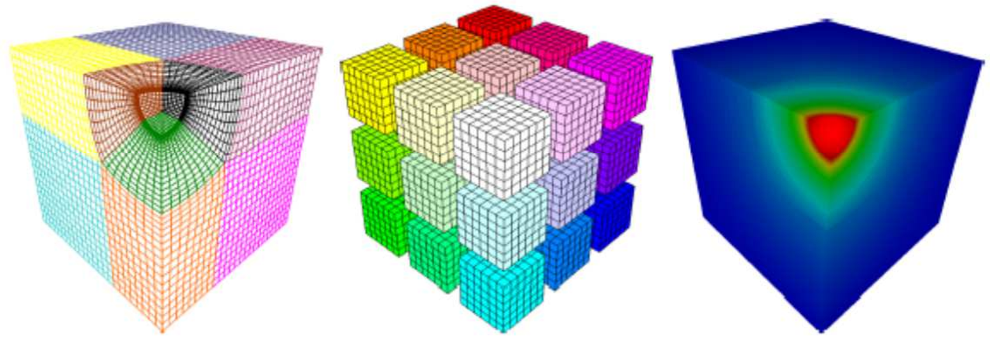
- Plasma simulation using macroparticles in self-consistent fields
- Solves the **Vlasov-Poisson equations** using the **PIC method** ...

$$\frac{\partial f_\alpha}{\partial t} + \mathbf{v}\cdot\nabla_{\mathbf{x}} f_\alpha + \frac{q_\alpha\left(-\nabla\phi + \mathbf{v}\times\mathbf{B}_0\right)}{m_\alpha}\cdot\nabla_{\mathbf{v}} f_\alpha = 0$$

$$-\epsilon_0\nabla^2\phi = \rho = \sum_\alpha q_\alpha \int_{\mathbf{v}} f_\alpha d^3\mathbf{v}$$



... on a **logically mapped curvilinear mesh** using **fast methods**



(a) Curvilinear (b) Logical (c) Solution

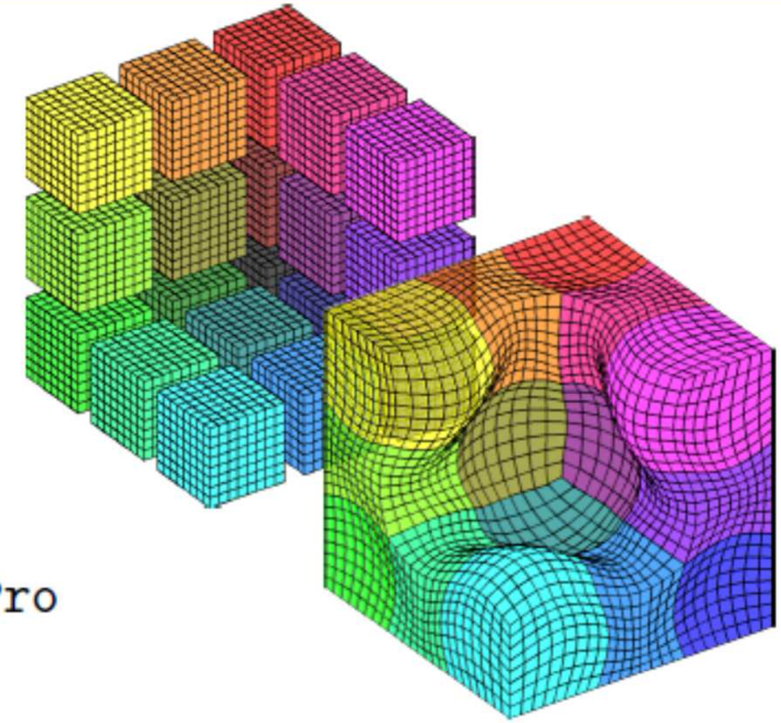
- Structured logical mesh
  (Faster solver, mover)
- Multigrid Solver
  (Near-optimal scaling)
- Hybrid particle mover:
  (No tracking, >5x **faster**)

- **Main Features**: Accurate, Scalable, Flexible

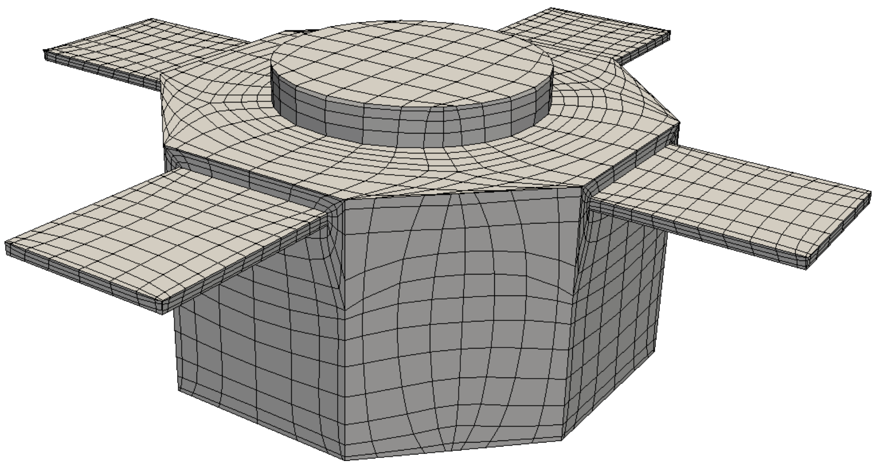
National Nuclear Security Administration

POC: Gian Luca Delzanno, delzanno@lanl.gov

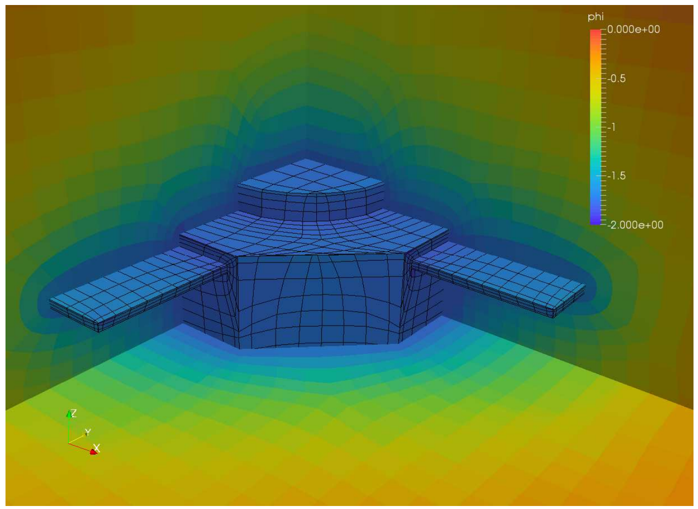
Multi-block CPIC:



- **Multi-block CPIC successfully developed and tested for charging on a sphere in a plasma**
- **Initial simulations with Van Allen Probes geometry performed**
  - **Accurate**, **detailed** models of S/C
  - Params from `SWMF`; mesh from `GridPro`
  - Highly parallelized, typical runs yield charging equilibrium in few hours



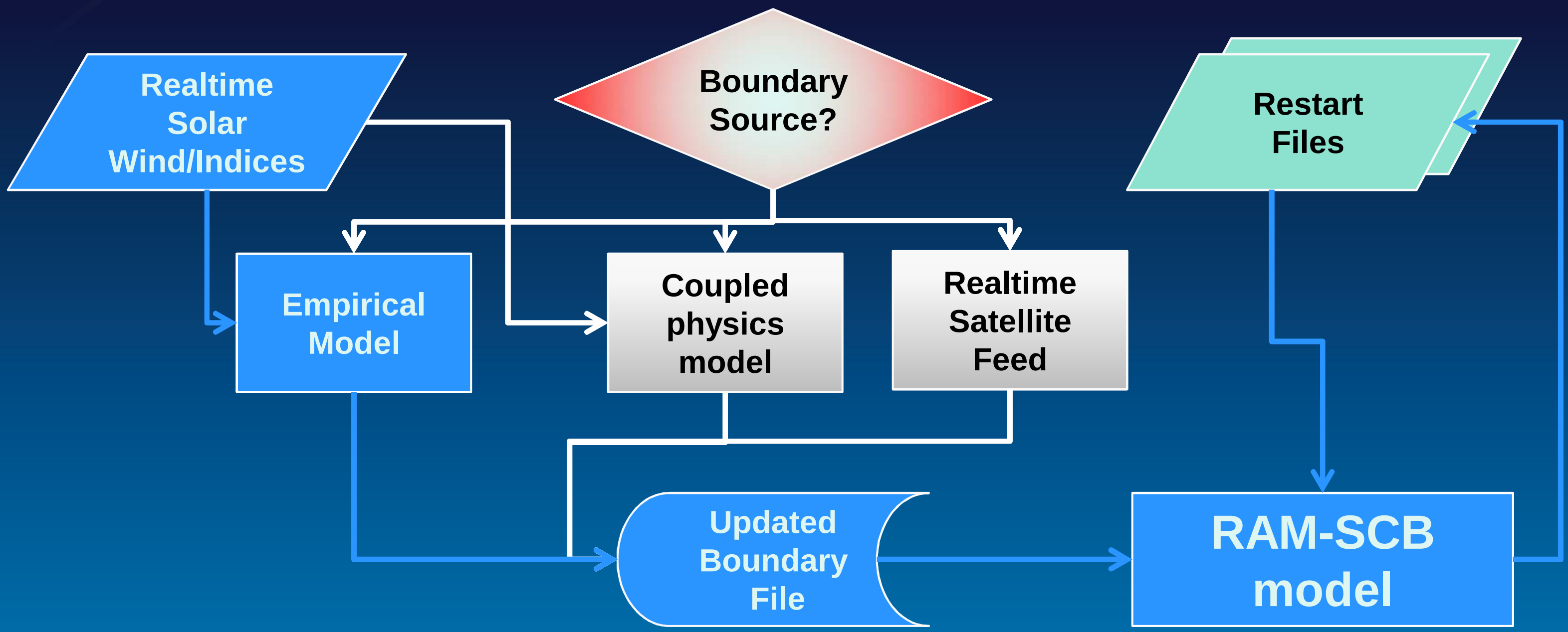
(d) Mesh



(e) Potential

Near Real-Time SHIELDS-RC Operation

Data and Software Block Diagram



- Development of a Real-Time SHIELDS capability, a simplified RAM-SCB model driven by solar wind conditions
- Given appropriate upstream solar wind measurements, the model provides a forecast of the SCE with a ~1 hour lead time

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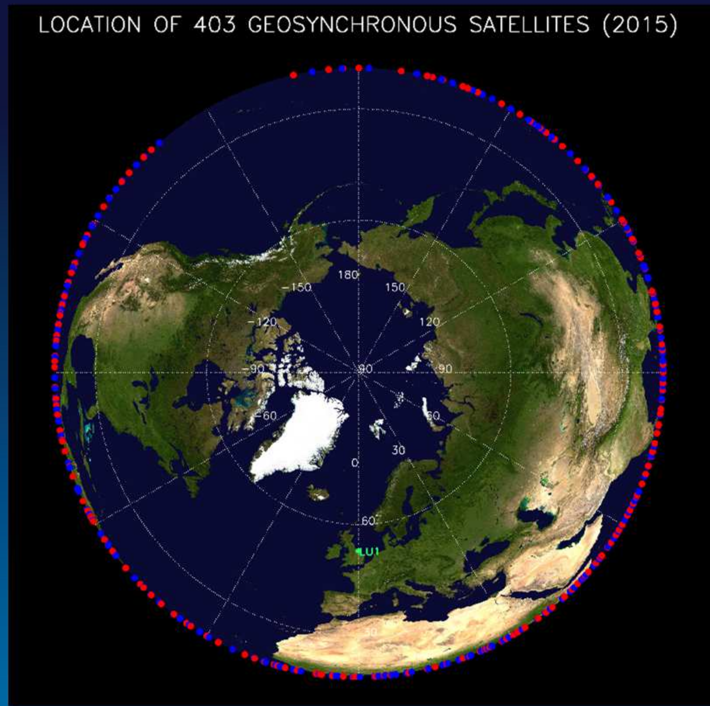
SHIELDS Impact

Computer, Computational, and Statistical Sciences Division CCS

Theoretical Division

U. Michigan

- Space weather research is rapidly gaining public recognition since economically important decisions could be made as the accuracy of space weather forecasts improves
- A unique space weather model will position LANL as a world leader in Space Situational Awareness and forensic analysis of space system failures
- Organizing a workshop in Santa Fe (NM) in September 11-14, 2017, on “Active Experiments in Space: Past, Present and Future” (POC: Delzanno@lanl.gov)
- Building strategic partnerships with other agencies (DOD, NOAA, NASA, NSF, FAA), institutions (Aerospace, universities), and commercial customers (satellite operators, etc.)



Approximate location of over 400 military, scientific, and communications spacecraft orbiting at GEO - projected to the Earth’s equator [Denton et al. *Space Weather*, 2016].

- **Website with lists of presentations and publications: http://www.lanl.gov/projects/shields/**

Backup Slides

40-minute 3D Hall MHD and MHD-EPIC Simulations

Hall MHD

Hall MHD-EPIC

- A 3D simulation of Earth's dayside reconnection (PIC region shown with red box)
- The coupled BATS-R-US with iPIC3D code produces very reasonable results and there are no significant numerical artifacts at the boundaries of the PIC region

Near Real-Time SHIELDS-RC Operation

Sample Model Output

The operational SHIELDS-RC provides output along specific satellite trajectory in the inner magnetosphere, example shown for the Van Allen Probes:

- ❖ Drivers (Vsw, Bz) and Kp & Dst indices as a function of time
- ❖ Electron energy spectra from ~1 to 350 keV
- ❖ Electron flux at 10 keV as an indication of SCE hazard