Characterizing Particle Dynamics from a Data-Driven Model of the Inner Magnetospheric Electric Field

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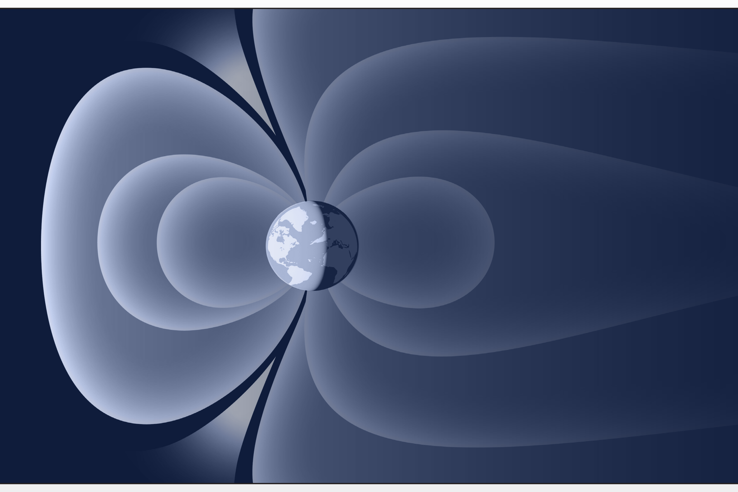

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Motivation

We are in development of a **dynamic, neural-network driven inner-magnetospheric electric field (IMEF) model** with the aim to advance the state of physics-based modeling of the magnetosphere through improved accuracy and predictive capabilities.

- The behavior of the inner-magnetosphere is an important link in the chain of energy transfer within the total solar-terrestrial system.
- Machine learning as a geospatial modeling tool has already been used with remarkable success reconstructing the evolution of magnetospheric plasmas[1]
- This model will extend on the foundation of the UNH-IMEF model, which presented enhanced performance overall when compared to other models, but still did not reproduce all characteristics of the data[2,3]

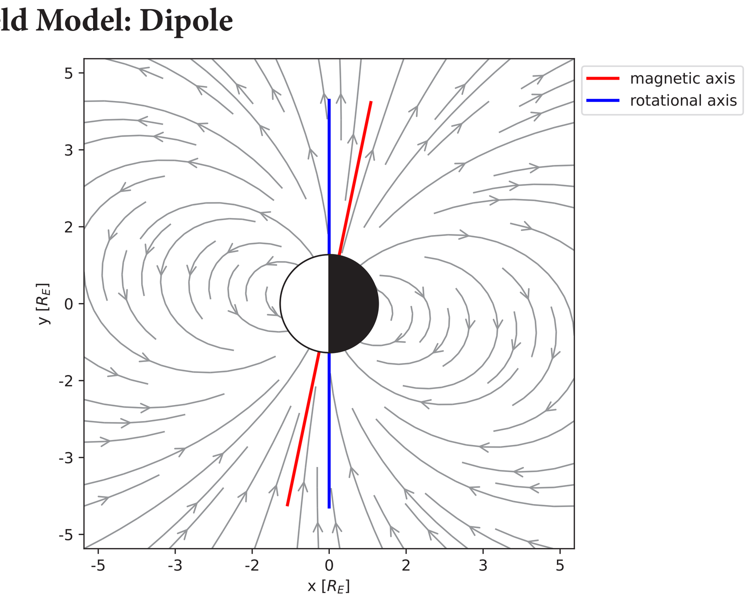
Methodology

Current efforts are focused on characterizing particle dynamics within the inner edge of the plasma sheet that require following components to be obtained:

1. A global magnetic field model
2. Electric field measurements from MMS Electron Drift Instrument (EDI)
3. Electric field line mapping under assumption of equipotentials B-field lines
4. Discretization algorithm for computing change of particle position, velocity, and energy over time

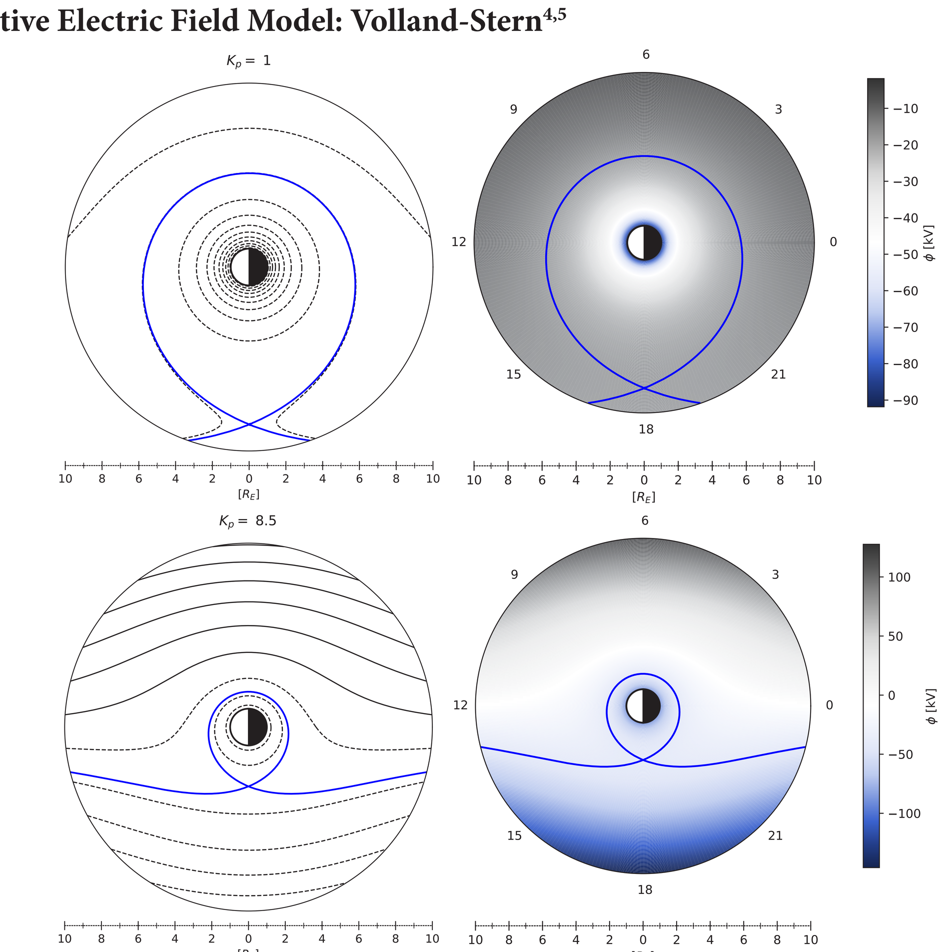
Electromagnetic Field Models

Global Magnetic Field Model: Dipole



Dipole model of Earth's Magnetic field

Comparative Electric Field Model: Volland-Stern[4,5]



Volland-Stern potential contours and color map for $k_p = 1$ (top) and $k_p = 8.5$ (bottom). Blue line indicates last closed potential (LCE)

Data-Driven Model

Determine electric field around Earth at any time, we trained a **3-layer neural network**, using a method similar to (Bortnik et al. 2016), that uses location data and 5 hours of geomagnetic index data to predict the electric field.

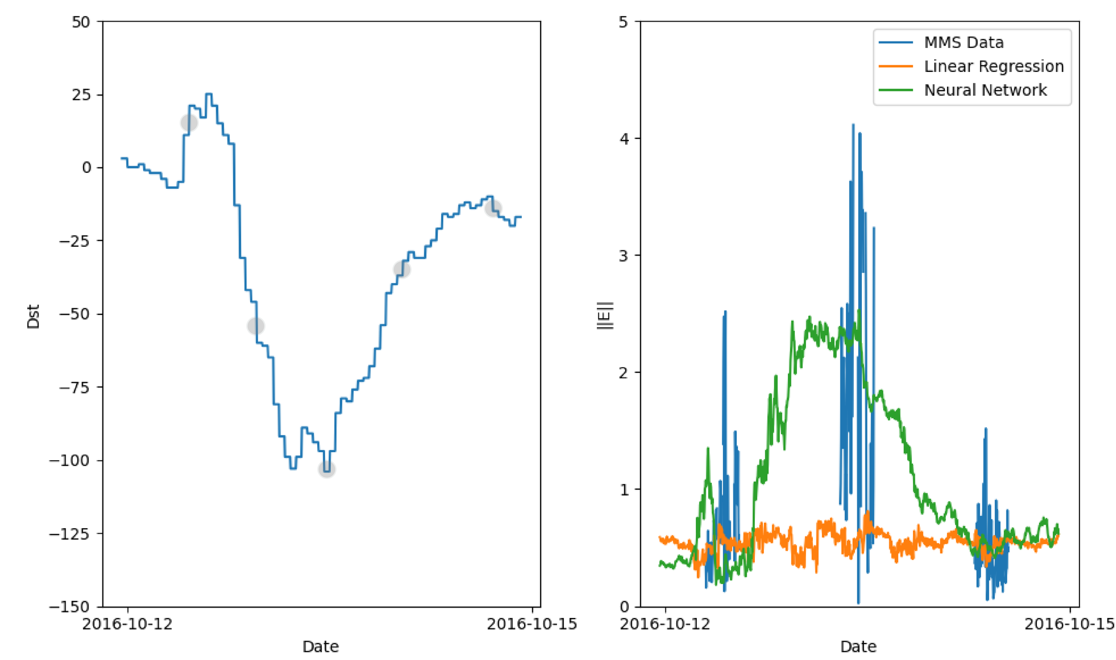
Electric field training data approximated through solving the **inverse problem**:

- EDI data cleaned and binned by radial distance from the Earth (L) and angle (MLT)
- Equation inverted by defining a loss function and determining minimum value
- Geomagnetic index (e.g. Dst, Kp index) and/or solar wind driver used to crudely determine good indicators of activity in inner-magnetosphere

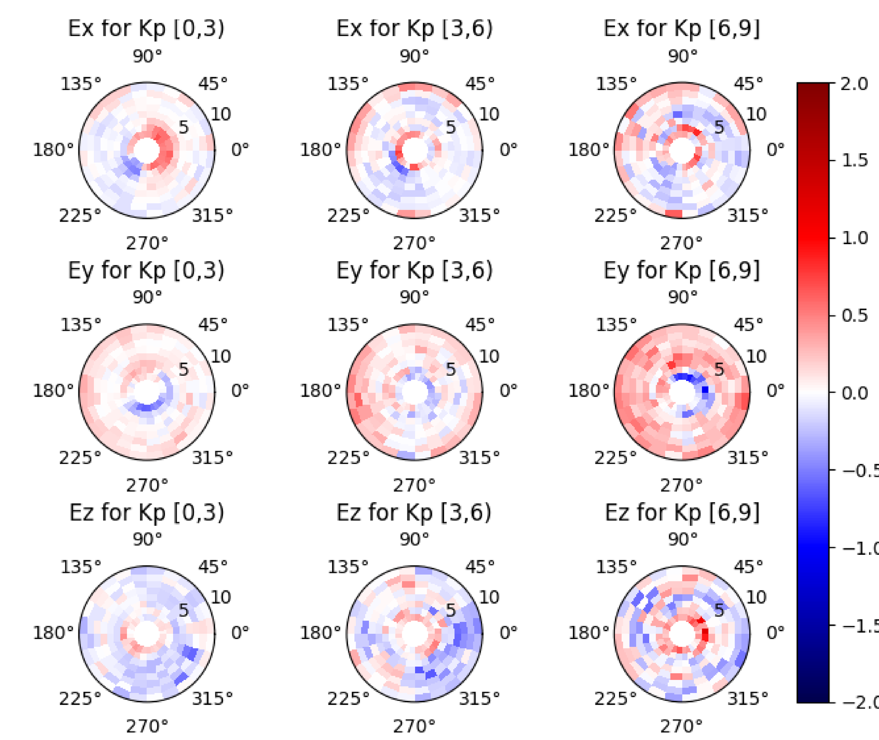
Creation of electric field map uses Field Line Mapping and follows two-step process:

1. Obtain E-field measurements in the orbital plane over aprox. 7 years from the MMS EDI Data
2. Map the E-field to all points along the magnetic field

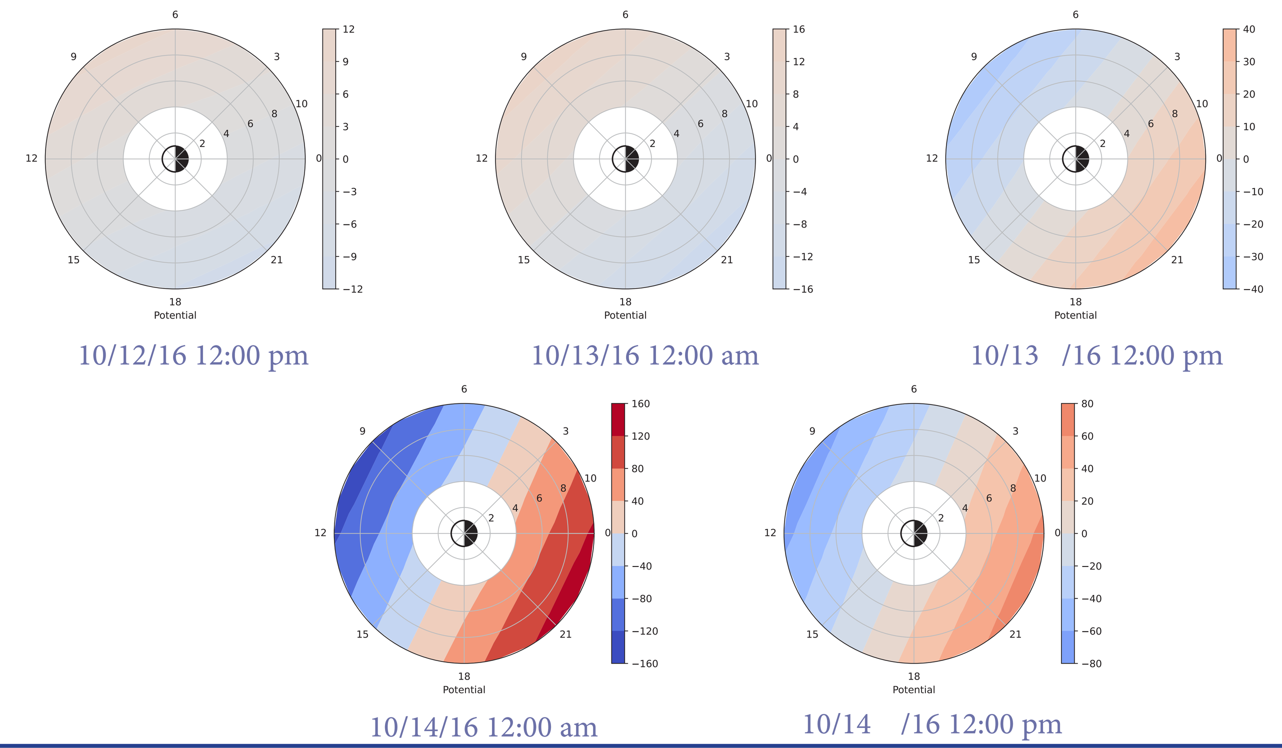
★ **Assume magnetic field lines are equipotentials** such that potential ($V=ExB$) is constant along field lines.



Electric field measured by MMS (blue), predicted electric field values from linear regression (orange), and predicted electric field values from the neural network (green)



Average x, y, and z-components of electric field in [mV/m] separated by k_p index



(Left): Evolution of the convective electric field during evolution of geomagnetic storm on Oct. 13-16, 2016.

- Electric field begins to intensify during main phase
- Does not fully reach pre-storm values by end of recovery phase

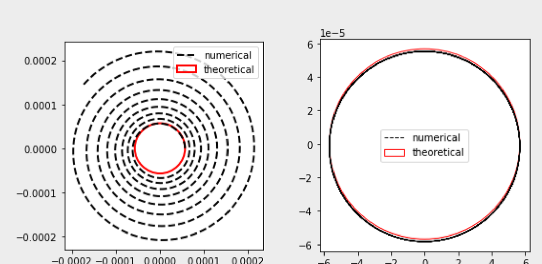
Charged Particle Motion

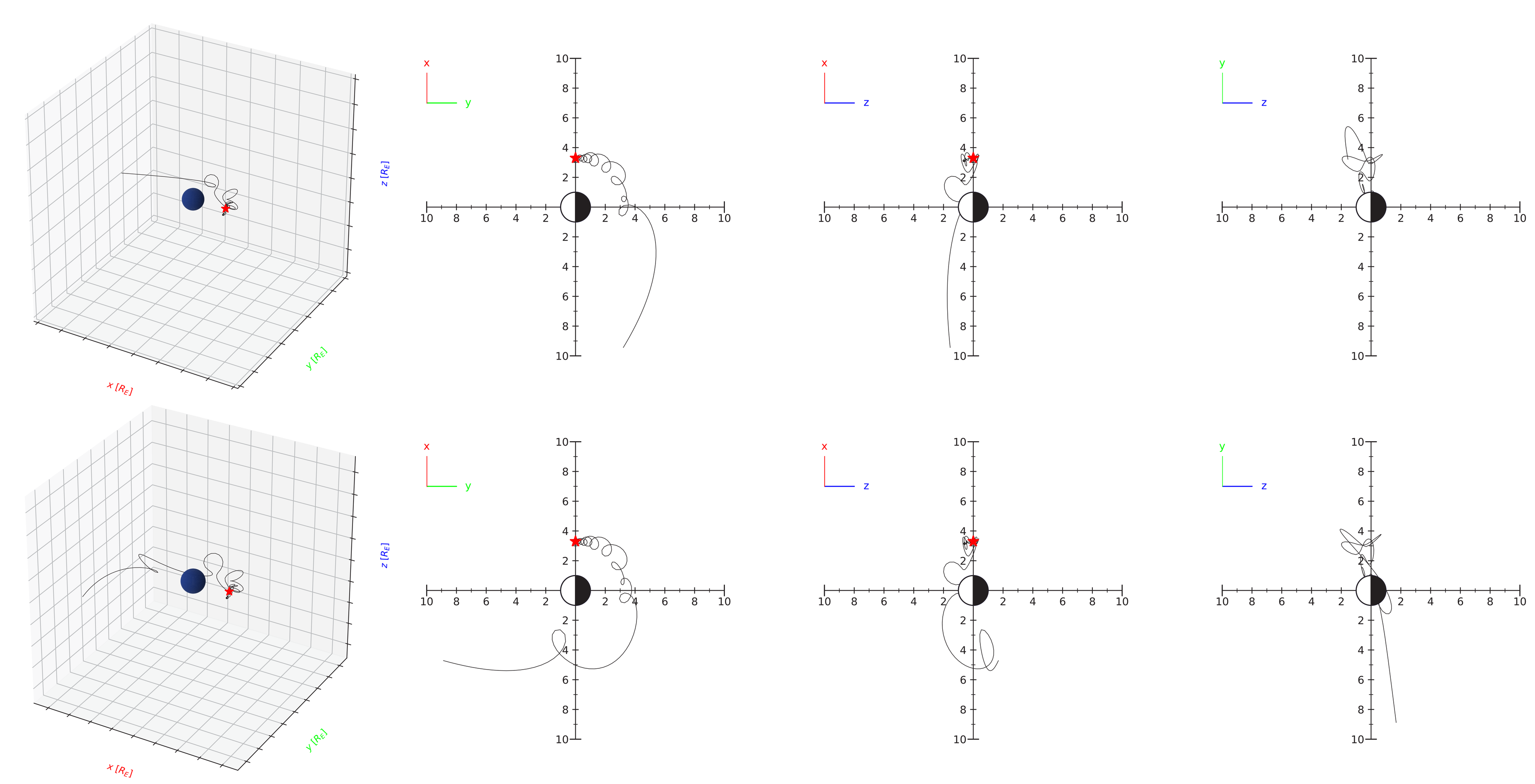
The motion of a particle with mass m and charge q is defined by the Newton-Lorentz Force (Relativistic Lorentz):

$$\frac{\mathrm{d}(\gamma m\mathbf{v})}{\mathrm{d}t} = q\mathbf{E}(\mathbf{r}) + q\mathbf{v}\times\mathbf{B}(\mathbf{r})$$

Determining the evolution of particle position over time by solving the **Boris Particle Pusher**

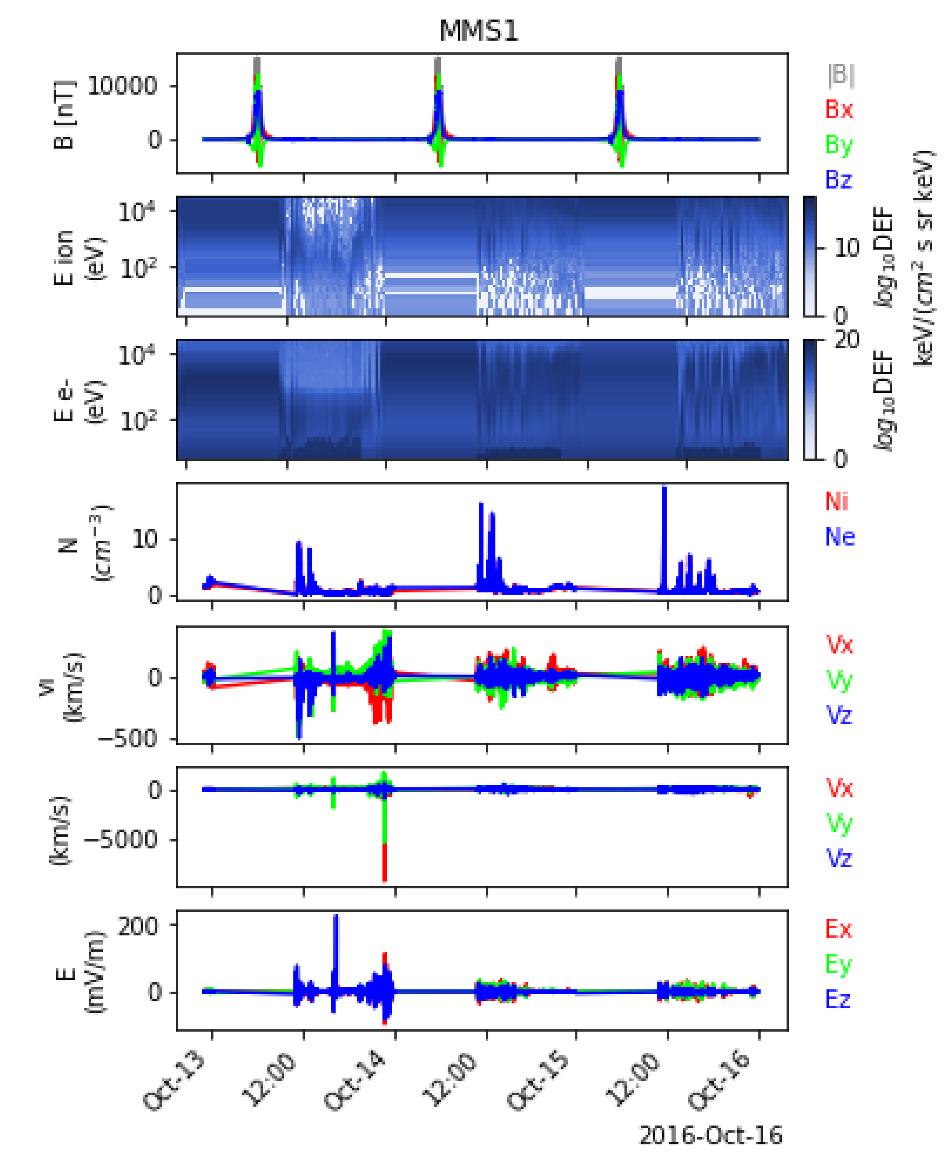
- Chosen due to its speed, efficiency, and notable volume-preserving properties[6]; similar methods, such as forward difference, can artificially inflate the energy.
- Particles traced backward in time give initial velocity and position provided by MMS data of geomagnetic storm event.





Backwards tracing results in 3D isometric view and 2D profile views for $k_p = 8.5$ with energy $E = 50$ kev (top) and 40 keV (bottom)

Geomagnetic Storm: Oct. 13-16, 2016



Geomagnetic storm overview plot of MMS data from October 13th, 2016, to October 16th, 2016.

Future Work

- Write-in other comparative electromagnetic models for model validation, such as the Weimer 96 and UNH-IMEF electric field models, and the IGRF and Tsyganenko magnetic field models
- Compare tracing results to developed model for different periods of geomagnetic storms
  - 27-30 May 2017, 6-12 Sep. 2017, and 25-30 Aug. 2018.

Acknowledgments

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