



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

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THE MAGNETOSPHERE

EARTH'S NATURAL DEFENSE AGAINST THE SUN

Protective
Shields our planet from solar ejecta (e.g. Solar Flares) and harmful radiation

Responsive
Shaped by Earth's molten core and constant bombardment of solar wind

The **electric field** is a key part of energy transfer dynamics and magnetospheric processes

Dynamic
A host to space weather events that can have an adverse effects on communication and space technology

Geomagnetic storms can lead to features such as aurora

BACKGROUND & MOTIVATION

The goal of this project is to analyze meso-scale phenomena by creating a novel inner magnetospheric electric field model with improved accuracy and predictive capabilities.

The inner magnetospheric convective electric field is a vital component energy transfer in the solar-terrestrial system.

- The solar wind drives global energy circulation within the magnetosphere which generates a global convective electric field.
- The convective electric field pushes the solar wind within the magnetosphere, transporting magnetic field lines and plasma across magnetospheric boundary. This results in ring current flows like Sub-Auroral Ion Drifts (SAID) and Subauroral Polarization Streams (SAPS), thus connecting to ionosphere and producing features like auroras.
- Global-scale characteristics of electric field well known, but uncertainty remains about how smaller meso-scale phenomena, such as SAPS, contribute to global response of geospace system.

To better study this phenomena, we are in development of a dynamic, neural-network driven inner magnetospheric electric field model with the aim to advance the state of physics-based modeling of the magnetosphere through improved accuracy and predictive capabilities.

- A completed model will allow for finer structures within the magnetosphere to be reproduced
- Machine learning as a geospatial modeling tool has already been used with remarkable success reconstructing the evolution of magnetospheric plasmas¹
- 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}

DATA-DRIVEN MODEL

Given a sequence of electric field measurements E_i at time t_i and three-dimensional location r_i , where $i=1, \dots, N$ and N is a large number, determine the distribution of E at every point within the model domain at time t and let the model evolve over time.

Predictors: Solar Wind Parameters from OMNI (V_x, y, z, B_z, D) and Geomagnetic Indices ($K_p, SYM-H, DST$) are used as predictors as they are good indicators of magnetospheric activity. Different groups of predictors are tested.

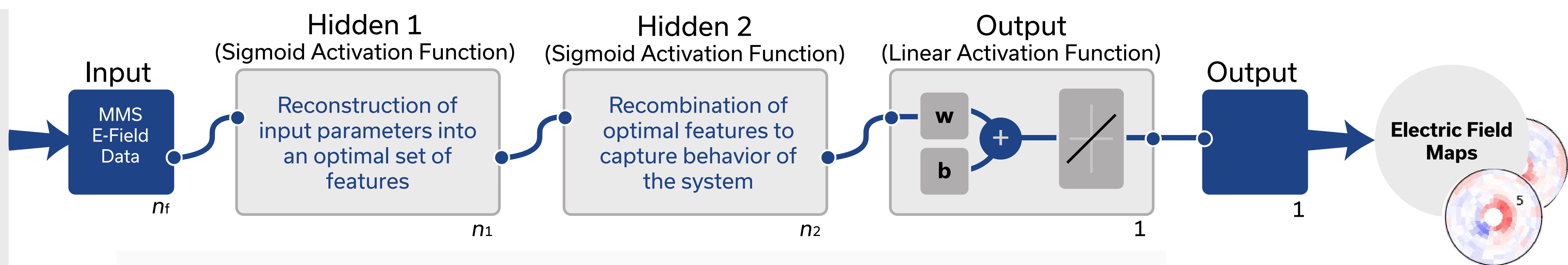


Figure 1: Schematic representation of neural network architecture used. Input contains n_f input parameters, with two hidden layers of n_1 and n_2 neurons, respectively, each having sigmoid functions. There is a single output neuron with a linear activation function.

MODEL DATA: MMS

Electric field data is taken from Electron Drift Instrument (EDI) and four dual ion spectrometers (DIS) on board NASA's Magnetospheric Multiscale (MMS) Mission.

- To determine the electric field around Earth at any time, we train 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 data E is sampled at different intervals (5min, 1min, 5s) to account for IMEF response times and resolve finer features
- To make the model dynamic, a time series will be used to regress the data and act as a reasonable predictor

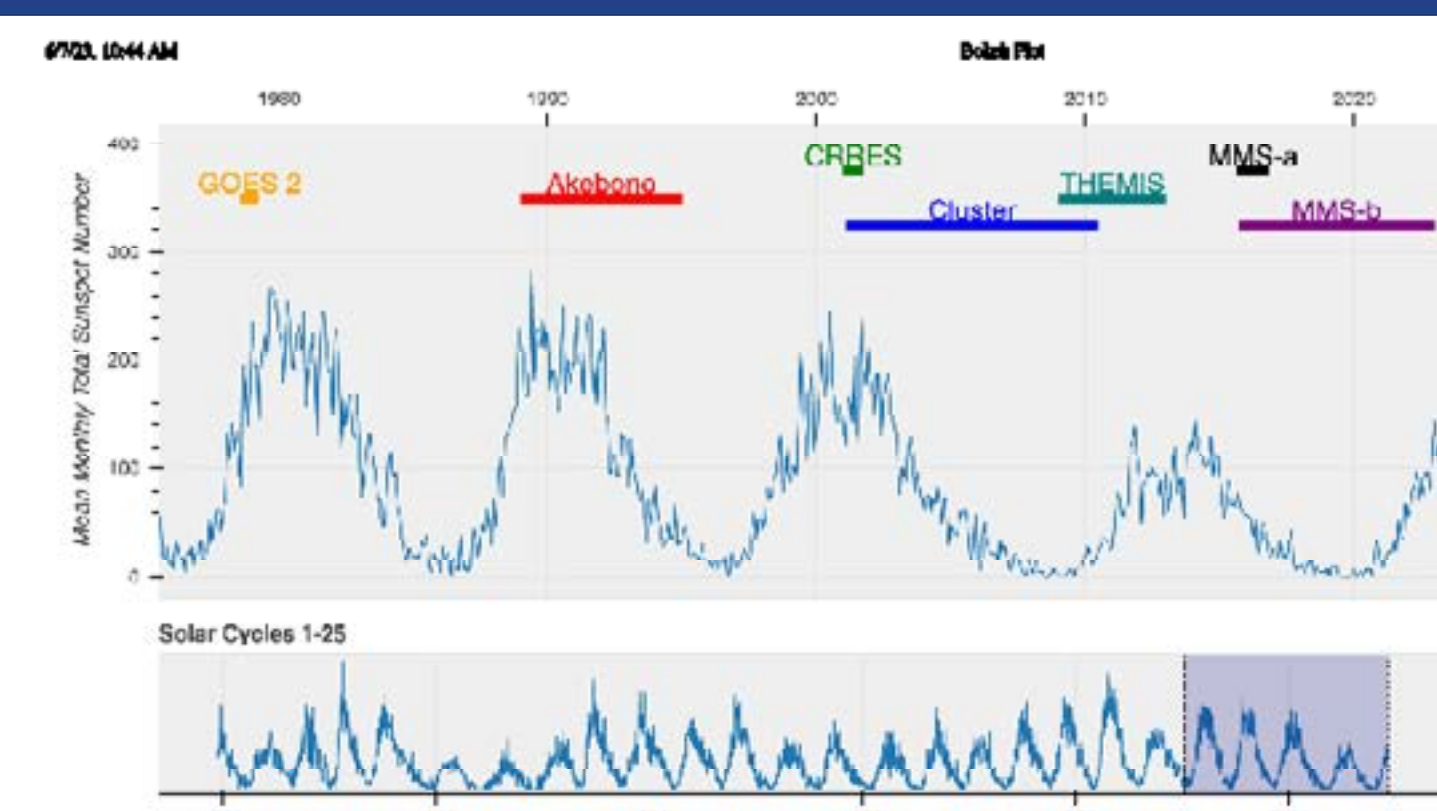


Figure 4: Plot of large-scale statistical studies of the IMEF are scattered over the last 5 solar cycles. GOES 2, Cluster, and MMS have an EDI instrument, where MMS is also entering a new solar maximum in solar cycle 25

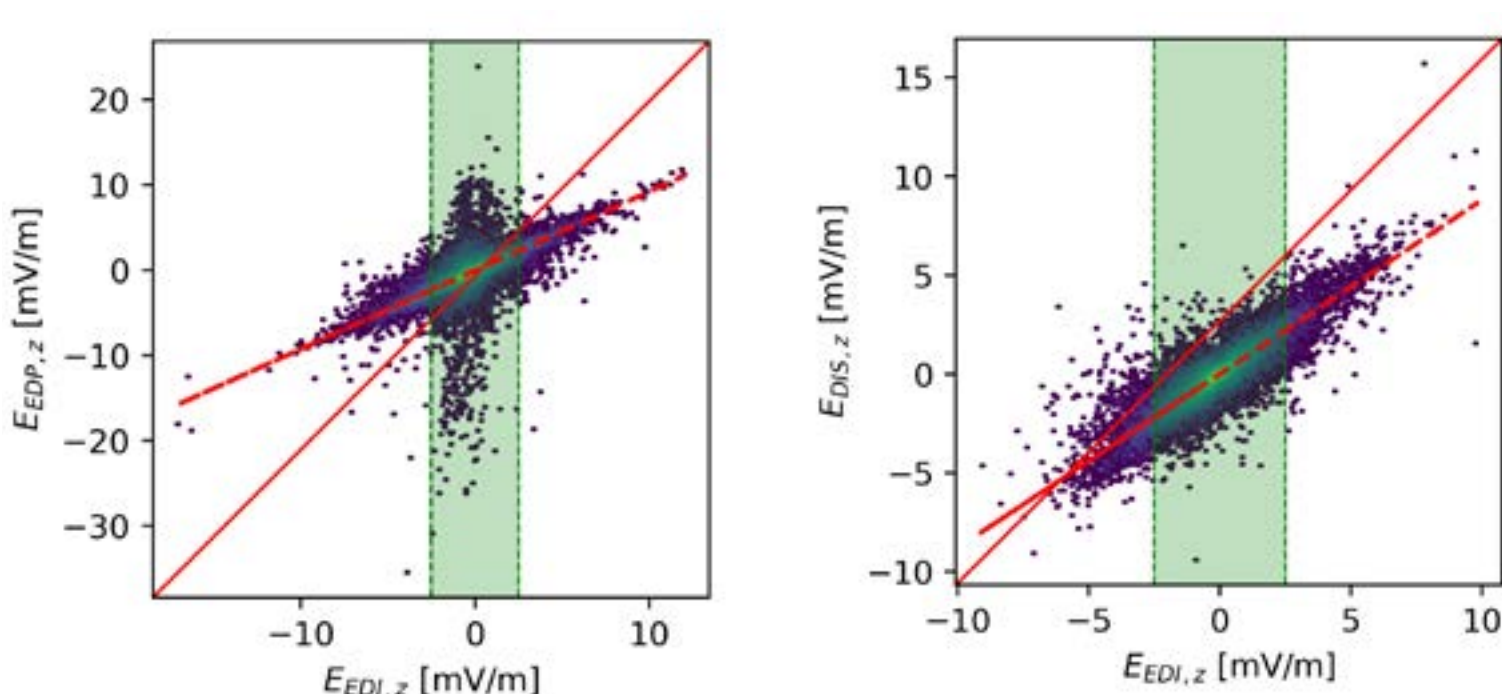


Figure 2: Comparison of electric field values to EDI values for the EDI and DIS MMS instruments from 2015-2020. Data measured on MMS-1. Plotted datapoints are grouped by hexagonal bins, or "hexbins," such that each hexbin denotes the log number of points, $\log(N)$, in it.

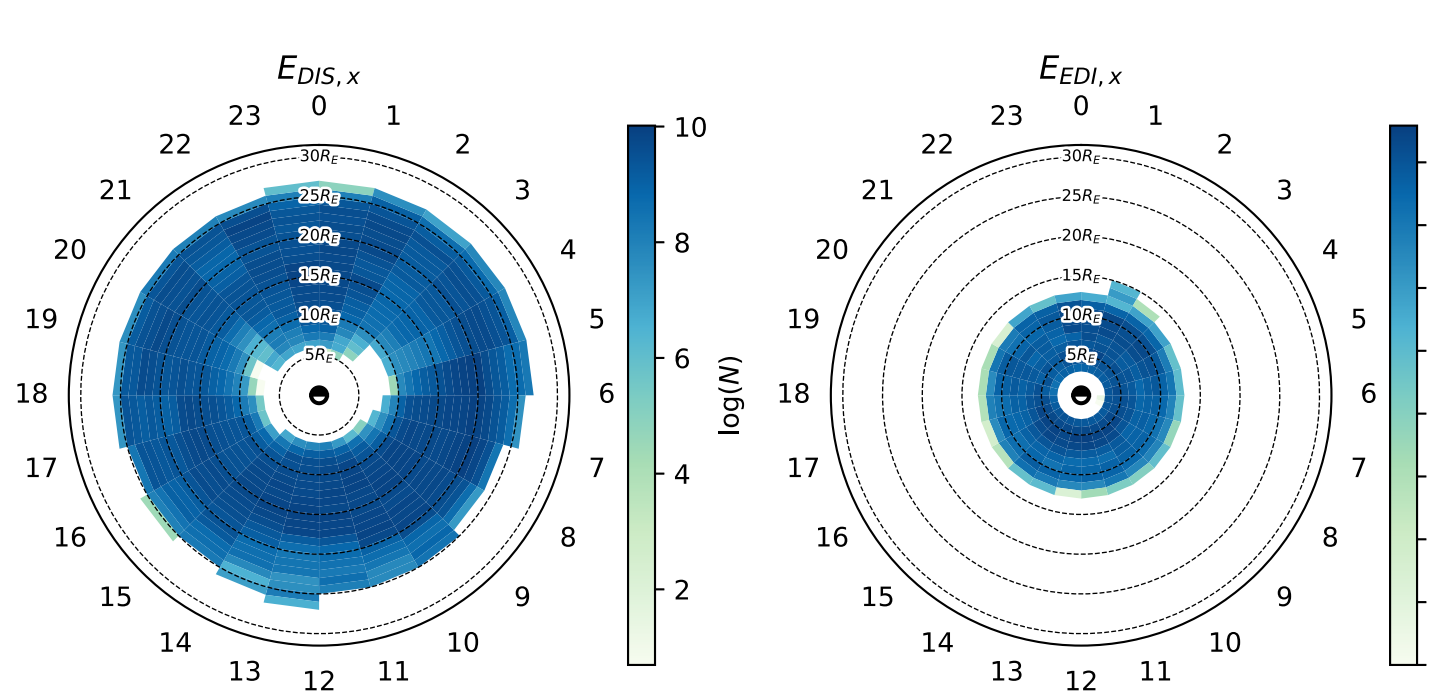


Figure 3: Coverage comparison of the DIS (LEFT) and EDI (RIGHT) MMS instruments. Plot is colored by $\log(N)$ number of data points.

EDI and DIS have complementary spatial coverage, especially in the critical flow breaking region

PROGRESS AND FUTURE WORK

Model outputs a 3D vector electric field that can be transformed into a 1D scalar electric field potential map by solving an inverse problem of $E = -\nabla V$ (Fig. 5,6). The current model is currently insufficient for producing fine-scale structures needed to study SAPS/SAID events.

- Numbers of neurons will be experimented with to optimize the model in conjunction with methods like GridSearchCV and Feature Ranking.
- The preliminary model uses only EDI data, and will need to add DIS data to address large data gaps.

- Cross-validation will also be used to compare different variations of the model.
- A time lag may also be introduced if model performance is not adequate.
- Other models may be explored, such as convolutional neural networks (CNNs) due to their translational invariance and are effective for time-series datasets with spatial relationships
- If more data is needed, there is potential to obtain data from other missions over various solar cycles (Fig. 4)

PRELIMINARY RESULTS

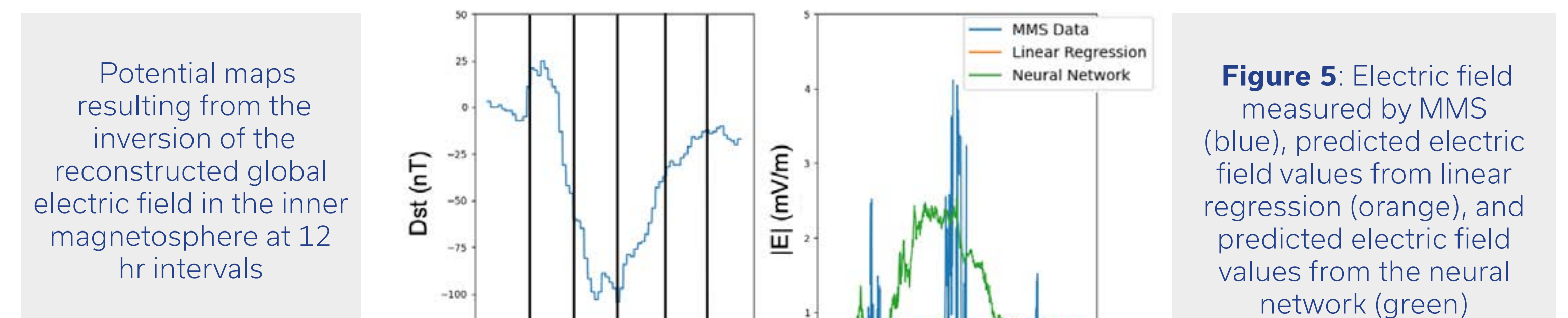


Figure 5: Electric field measured by MMS (blue), predicted electric field values from linear regression (orange), and predicted electric field values from the neural network (green)

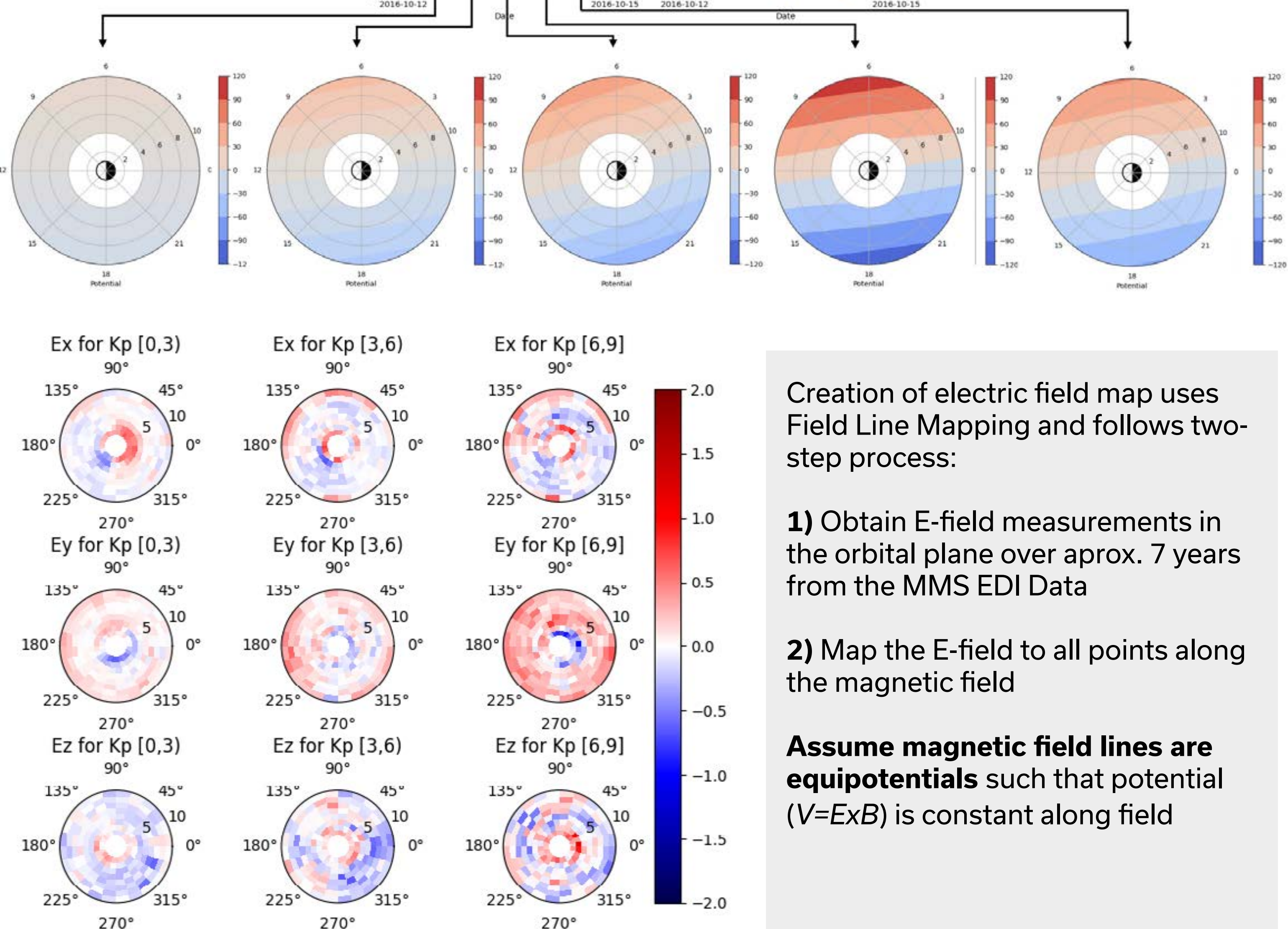


Figure 6: Plot of EDI measurements in each 1 MLT x 1 RE bin in the region $3 < R < 10$ RE from 2015-2022.

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

- 1) Obtain E-field measurements in the orbital plane over approx. 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

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