



Towards an Interpretable Machine Learning Model of Localized Geomagnetic Disturbances in Terms of Solar Wind and M-I Processes

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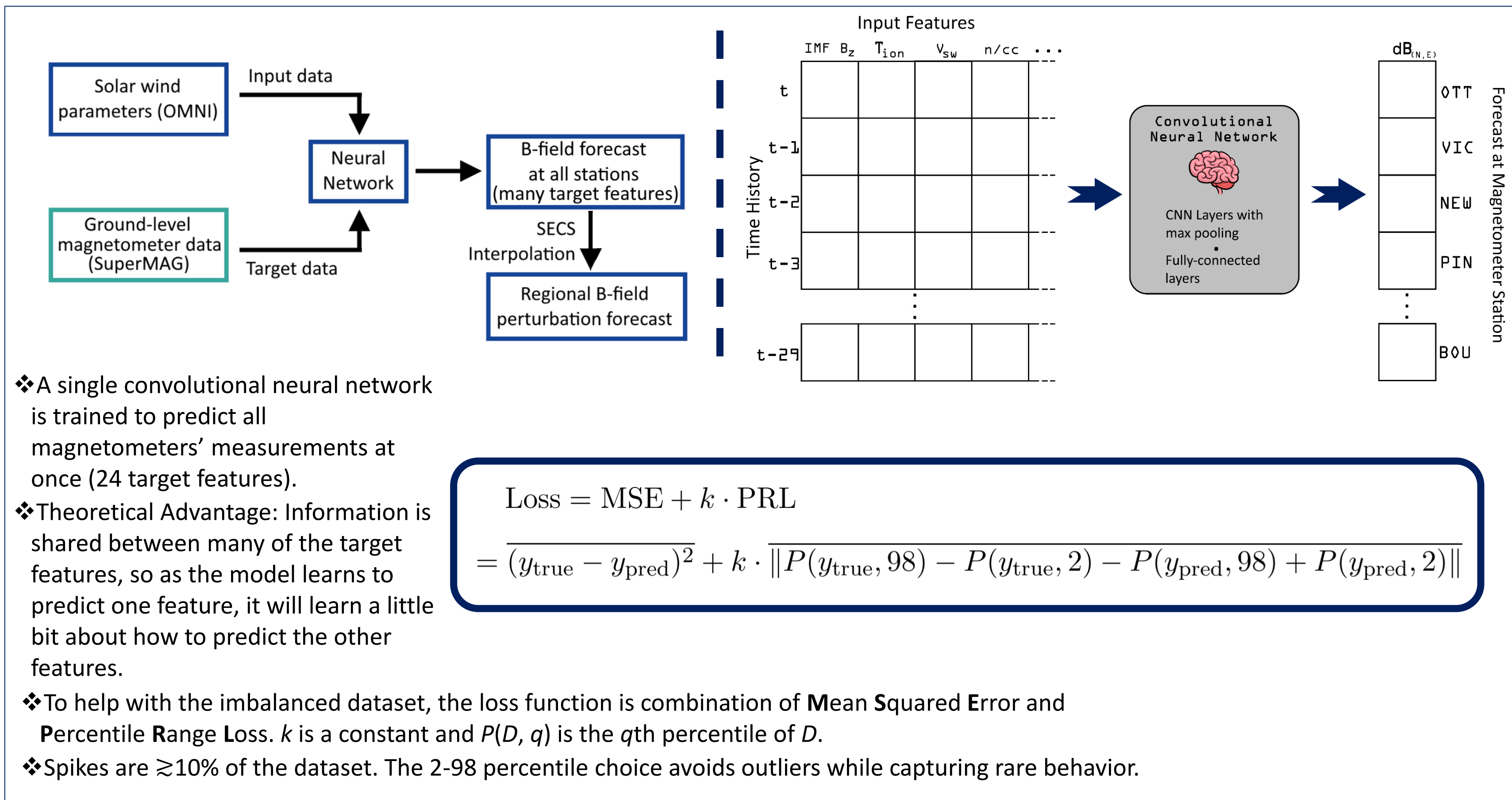
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Introduction

- ❖ The solar wind's interaction with the Earth's M-I system can cause Geomagnetically Induced Currents (GICs), which are hazardous to power and communications infrastructure.
- ❖ Fluctuations in the horizontal component of the background-subtracted ground magnetic field (dB_H) or its time derivative are used as a proxy for GIC measurements.
- ❖ The fluctuations are often spatially localized during geomagnetic storms. Sparse magnetometer coverage makes studying these fluctuations difficult.
- ❖ We used a neural network to model the physics that connects the solar wind to localized dB_H . Now we seek to modify the model for interpretability, eventually allowing us to explain localized areas of dB_H in terms of their M-I drivers.

Magnetic Multi-Target Prediction



$$\text{Loss} = \text{MSE} + k \cdot \text{PRL}$$

$$= \overline{(y_{\text{true}} - y_{\text{pred}})^2} + k \cdot \left(\|P(y_{\text{true}}, 98) - P(y_{\text{true}}, 2) - P(y_{\text{pred}}, 98) + P(y_{\text{pred}}, 2)\| \right)$$

The outputs of the neural network (dB_N and dB_E at each magnetometer station) are **spatially interpolated** in an electrodynamics-informed way to create a **forecast map over the entire region**.

Key Insights

- ❖ We have made progress towards a predictive model of dB_H across an entire region.
- ❖ The CNN model performs much better with very low initial learning rates ($\sim 10^{-9}$) with the Adam optimizer. This is because the large number of target features creates a "spiky" loss landscape.
- ❖ The loss is calculated from multiple target features by taking its mean across each target feature. This may destroy information that another loss function might preserve.
 - ❖ What are some possible alternatives?
- ❖ Other architectures will be investigated, e.g. XGBoost or chained multi-target regression.
- ❖ So far only solar wind inputs are used. The next iteration will include ionospheric data from sources such as DMSP and AMPERE.
- ❖ Special steps must be taken to avoid excessive linear correlation among output variables.

Spatial Interpolation with Spherical Elementary Current Systems

How can we estimate dB_H far away from magnetometer stations?

Spherical Elementary Current System (SECS) Interpolation. A hypothetical current sheet is constructed at ~ 100 km altitude. The vector field describing the current is expressed as a superposition of divergence-free basis vector fields, each centered at a different point on a latitude-longitude grid. In the superposition, each elementary basis field has a strength coefficient. We tune the values of each coefficient so that the overall current sheet reproduces the B_N and B_E values at all magnetometers. The total current sheet is then related to the magnetic field via the Biot-Savart law.

❖ The magnetometer forecast vector (CNN output) is used to fit a grid of Spherical Elementary Current Systems, representing ionospheric currents.

❖ From these currents, we derive 1-minute cadence dB_H values across the region during storm time in Solar Cycle 24 (2009-2019).

❖ Interpolations are validated by leaving each station out 1 by 1 and at comparing at that station's site.

❖ The entire process is differentiable (though not learnable), which enables certain attribution methods such as DeepLIFT and Integrated Gradients.

❖ An automated algorithm identifies localized geomagnetic disturbances (**black contours**) in the prediction.

Acknowledgements

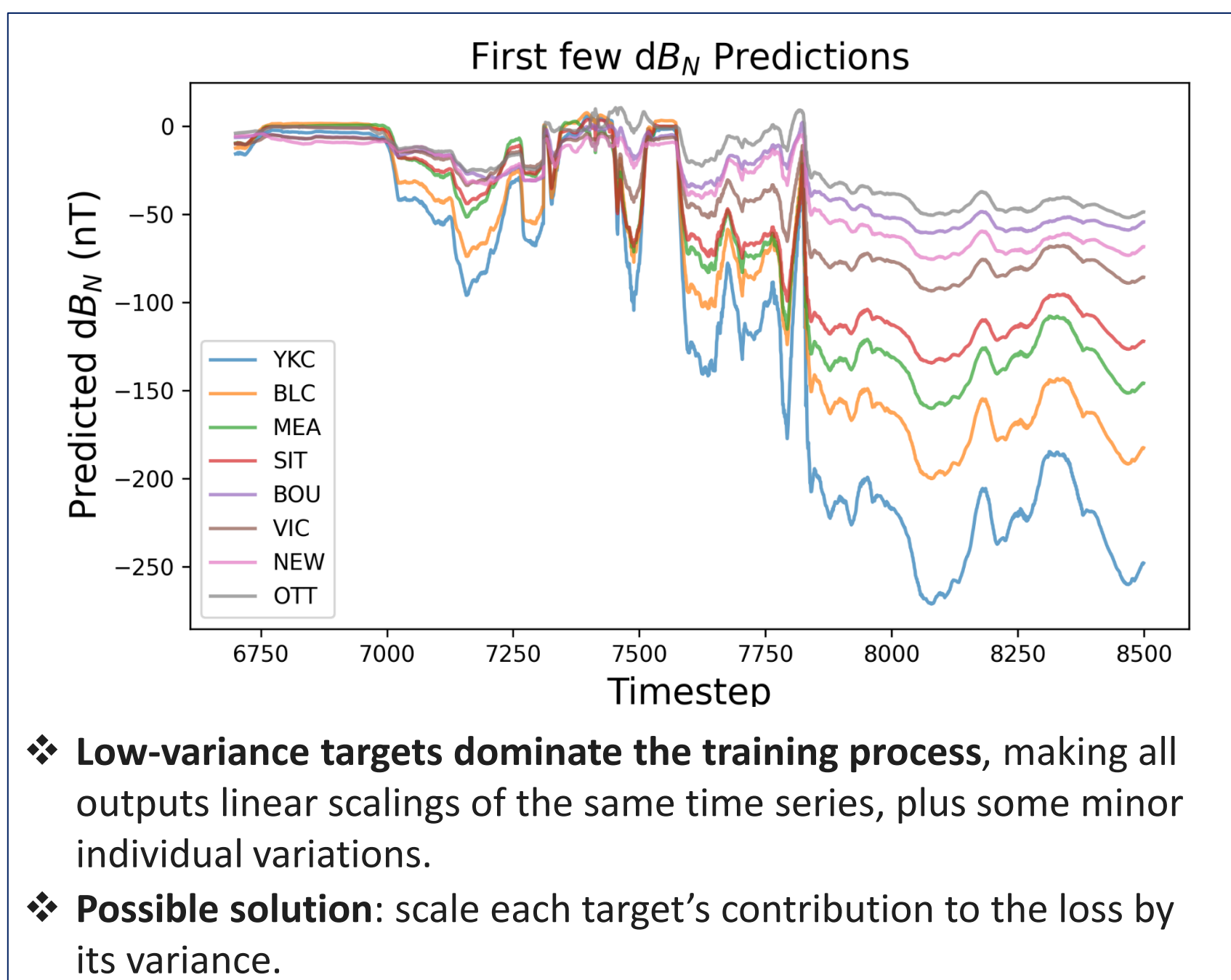
This work is supported by NSF EPSCoR T-2 Award 1920965 & NSF Award 2331527

❖ Amm & Viljanen 1999. *Ionospheric disturbance magnetic field continuation from the ground to the ionosphere using spherical elementary current systems.*

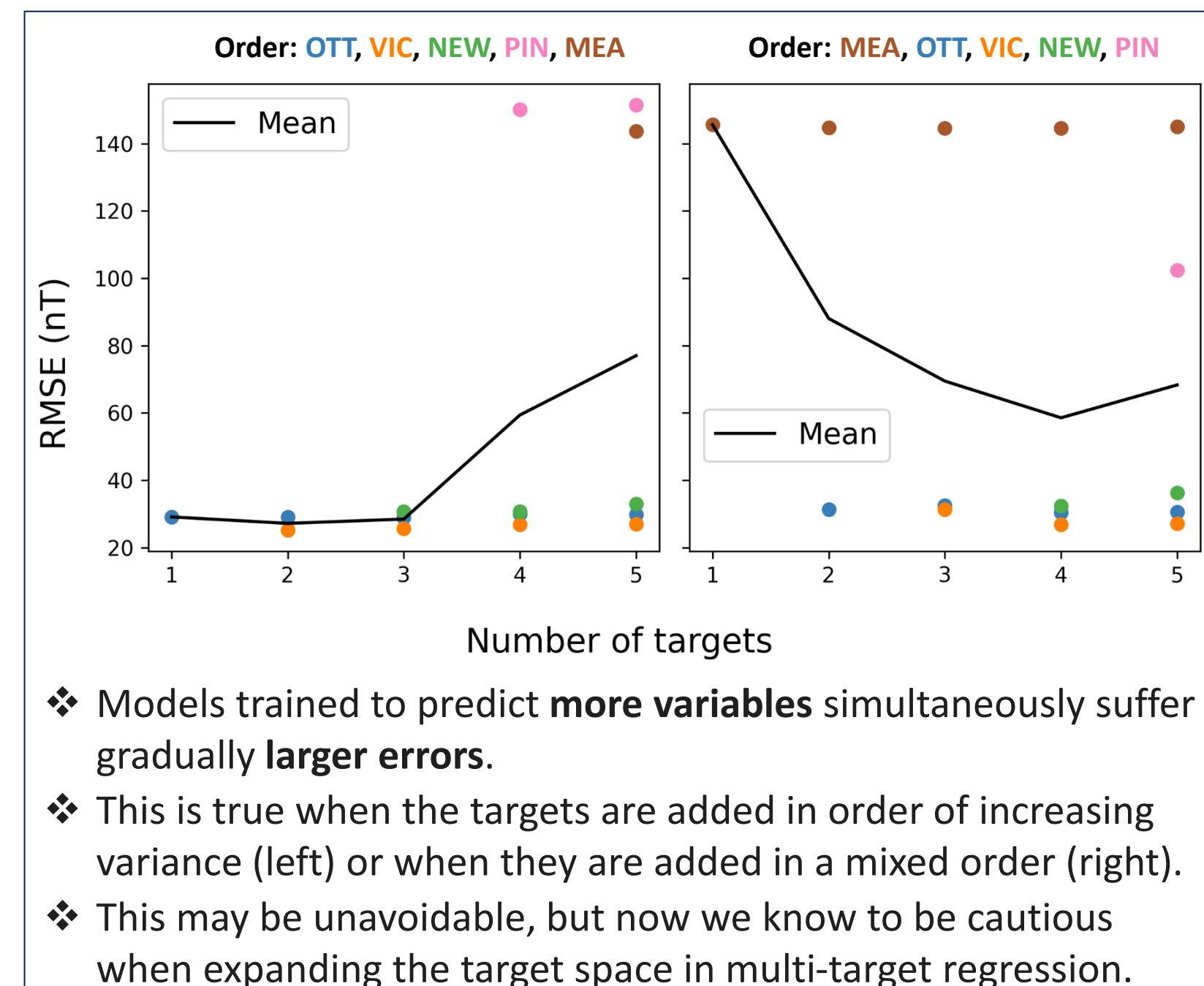
❖ OMNIWeb data from omniweb.gsfc.nasa.gov

❖ SuperMAG data obtained from supermag.jhuapl.edu

Predictions Become Highly Collinear



Fewer Targets = Better Performance



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