A SuperDARN-Based Validation Method for the REMIX Ionospheric Model by Assessing ExB Convection Patterns

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Abstract

Accurate **modeling** of **ionospheric electrodynamics** is crucial for understanding Earth's near-space environment and for **space weather forecasting** necessary to support mitigation of its impacts on critical infrastructure. This study introduces a promising method to validate **REMIX**, the ionospheric electrodynamics component of the Multiscale Atmosphere-Geospace Environment version **0.75 (MAGE)** framework, using high-resolution Super Dual Auroral Radar Network (**SuperDARN**) radar data, focusing **on ionospheric plasma convection**. This technique utilizes the **REMIX-calculated** electrostatic **potential** to **compute ExB drifts**, which are then interpolated to **SuperDARN range gate** locations determined using the pyDARN library. By projecting the modeled ExB convection onto radar beam look directions, we derive **expected line-of-sight velocities** that can be directly **compared with observed** SuperDARN velocities representing **F-region plasma convection**. This provides an approach to **identify discrepancies** between the **model** and **observations**, providing valuable insights for improving the accuracy and reliability of REMIX and enhancing our understanding of **magnetosphere-ionosphere coupling**. Initial comparisons highlight the method's potential for identifying such areas of agreement and disagreement. Future work will involve both **validating** the **REMIX**-derived convection patterns **using** the **SuperDARN convection mapping** algorithm and using the validated **REMIX model to generate statistical convection** patterns as a function of IMF clock angle.

Summary

- ❑ A method to **validate REMIX** .
- ❑ Uses REMIX potential to **compute ExB** drifts, which are then compared with **SuperDARN** radar line-of-sight **velocity** data.
- ❑ This comparison **identifies discrepancies**, aiming at improving REMIX accuracy, magnetosphere-ionosphere coupling understanding, and future statistical convection pattern generation.

Introduction

SuperDARN: Ionospheric Radar Network

❑ Global HF radar network for high-latitude ionosphere monitoring.

❑ Measures F-region plasma convection & studies space weather effects by detecting radio waves scattered by ionospheric irregularities under the Bragg condition.

❑ Doppler shift reveals ionospheric convection via assuming irregularities travel with background ExB drift:

$$\vec{v}_d = \frac{\vec{E} \times \vec{B}}{B^2}$$

MAGE: Modeling the Atmosphere-Geospace System

❑ First principles, physics-based framework for simulating atmosphere-geospace dynamics.

❑ REMIX is the Ionospheric Electrodynamics Solver which calculates electrostatic potential, currents, conductances.

❑ REMIX solves ionospheric Ohm's law (thin-shell approximation) driven by field-aligned currents from GAMERA, the geospace magnetohydrodynamics component.

Methods

Data Sources:

❑ SuperDARN fitacf data from March 17, 2015, for specific radar sites. Here Adak West is chosen.

❑ REMIX output from CCMC† over same period.

Processing Steps:

❑ Read and process SuperDARN fitacf files using pyDARN to obtain radar velocity measurements and range gate locations.

❑ Read MIX h5 files containing modeled electrostatic potential and other variables.

❑ Calculate ExB drifts from REMIX's electrostatic potential.

❑ E is derived from the potential and B is (currently) a dipole magnetic field.

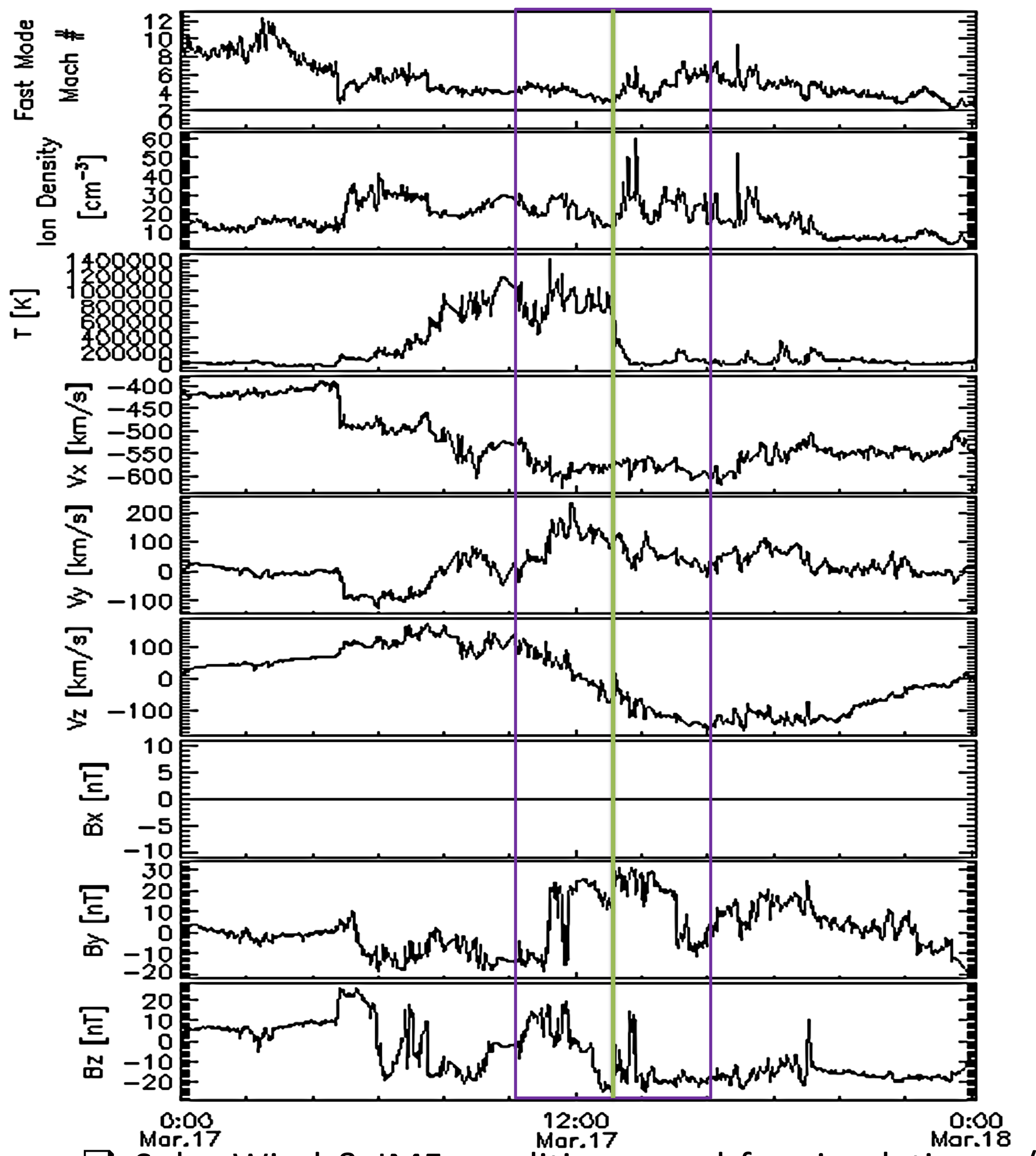
❑ Transform radar gate locations to Solar Magnetic (SM) coordinates.

❑ Interpolate modeled ExB drifts to radar gate locations using cubic interpolation.

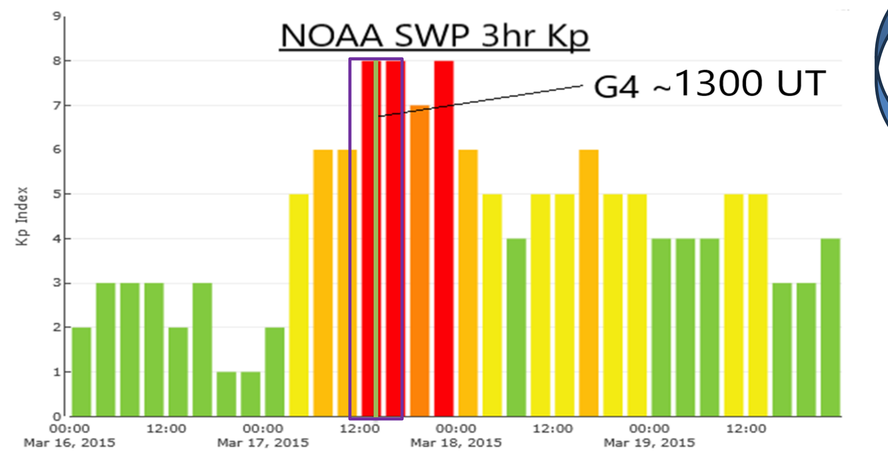
❑ Project interpolated ExB drifts onto radar beam look directions to compute expected line-of-sight velocities.

❑ Compare expected velocities with observed SuperDARN velocities to evaluate model performance.

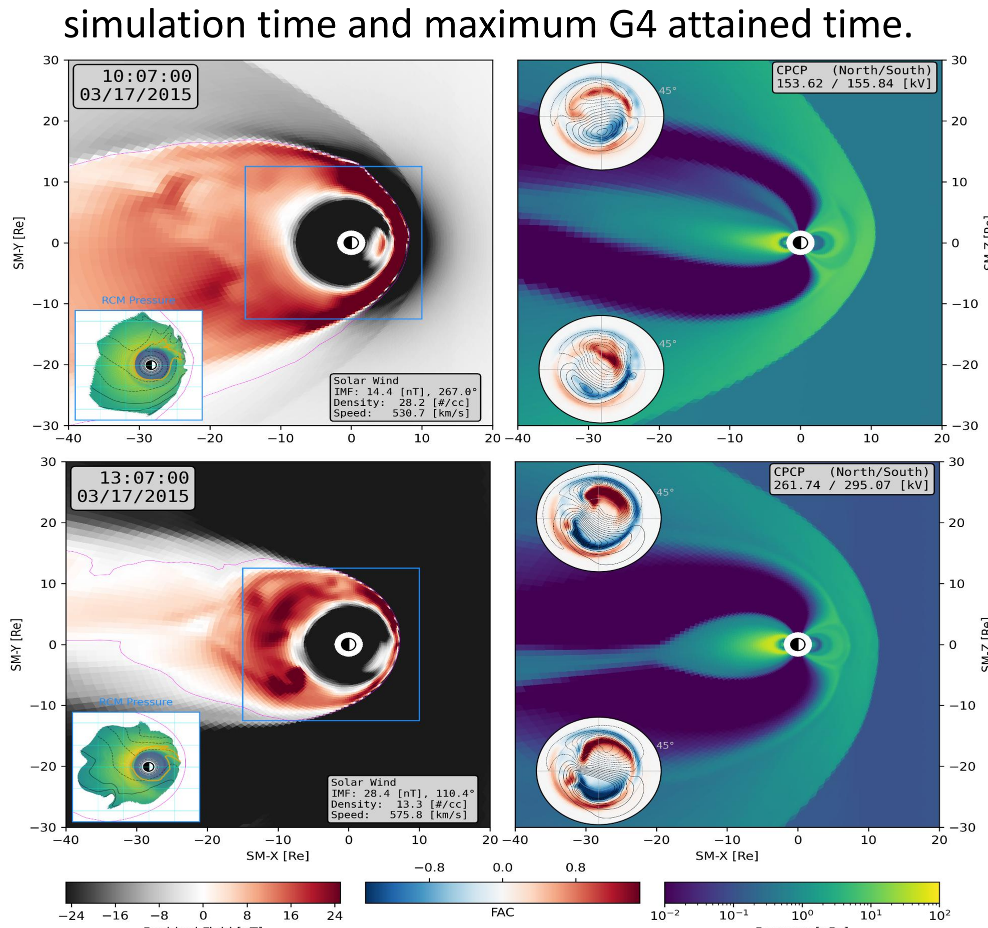
Event Info: 03/17/15



❑ Solar Wind & IMF conditions used for simulation w/ purple window showing inspection window and green line showing ADW radar velocity turning point.



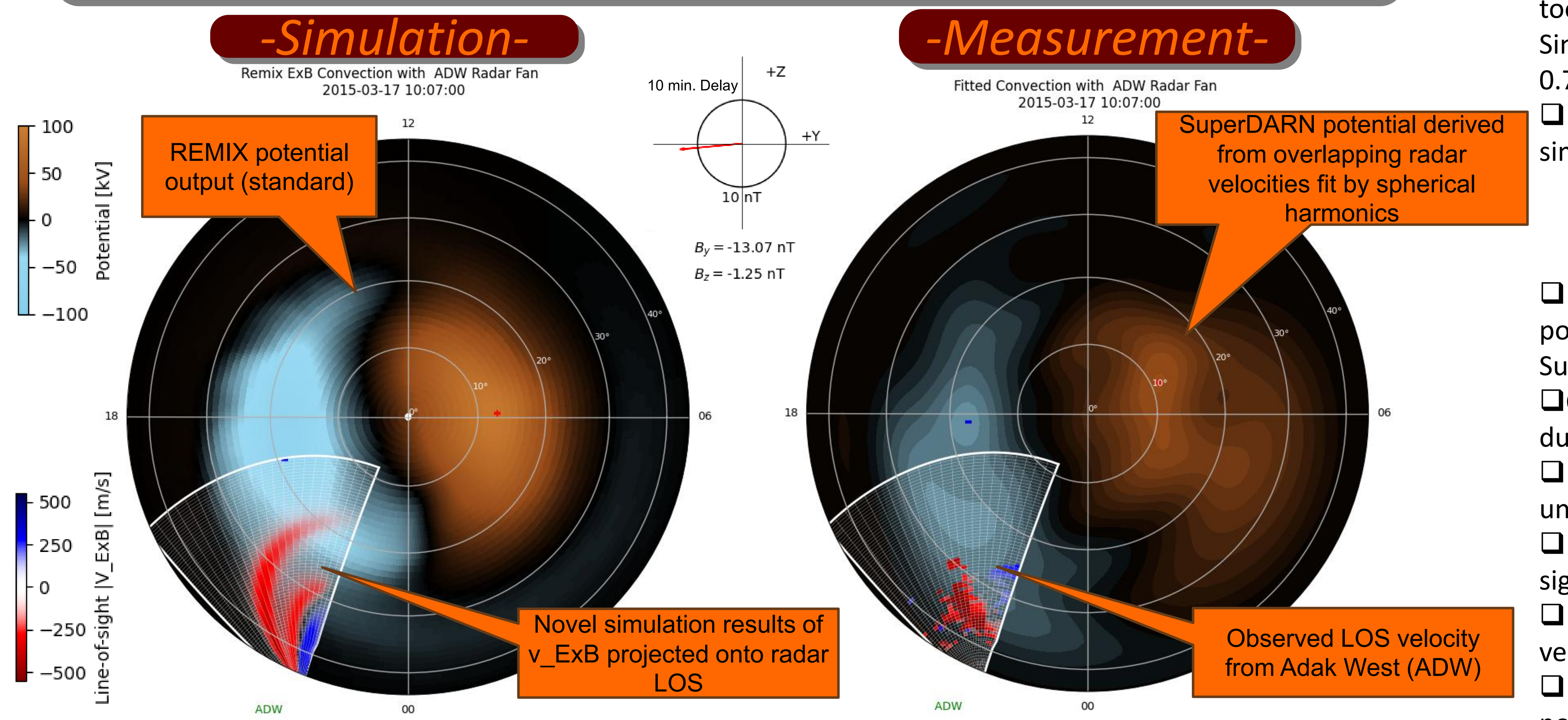
❑ Geomagnetic conditions characterized by Kp during simulation time and maximum G4 attained time.



❑ MAGE 0.75 simulation results at (Top) inspection window start and (Bottom) immediately after ADW radar velocity turning point.

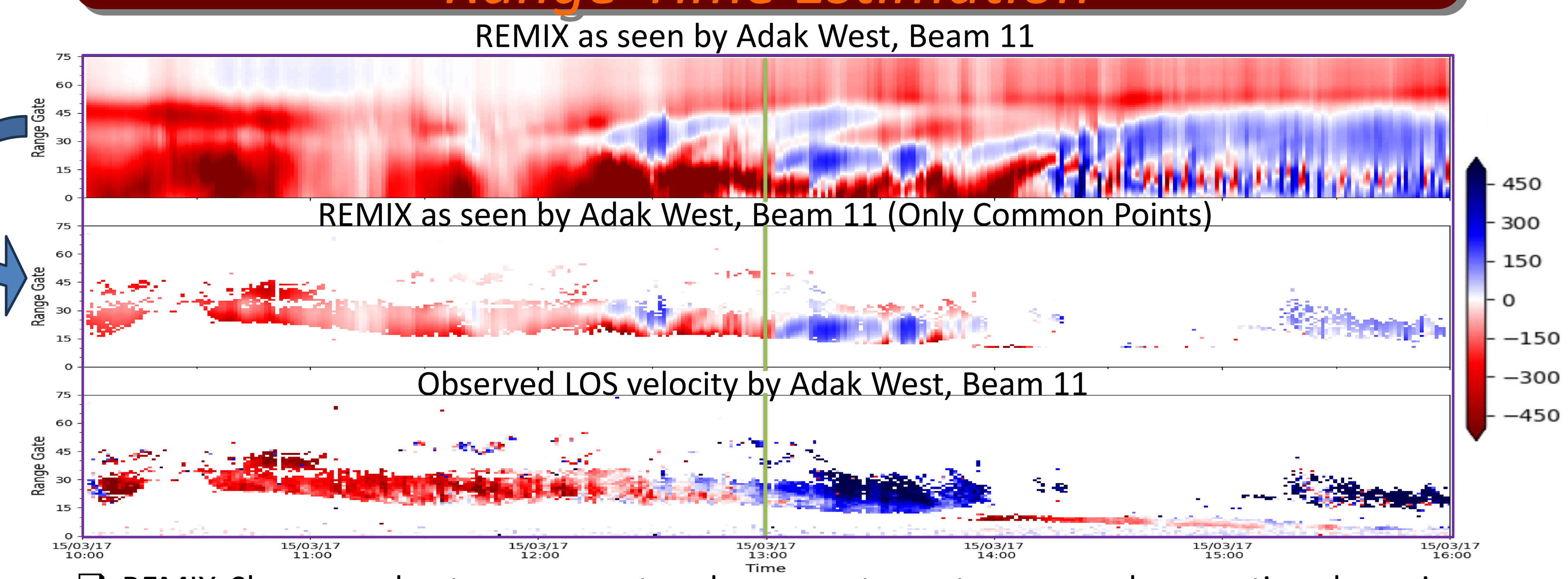
Results

--Potential & Convection--



❑ REMIX & SD MAP moderate electrostatic potential agreement, but Remix appears to overestimate (generally holds over entire simulation).

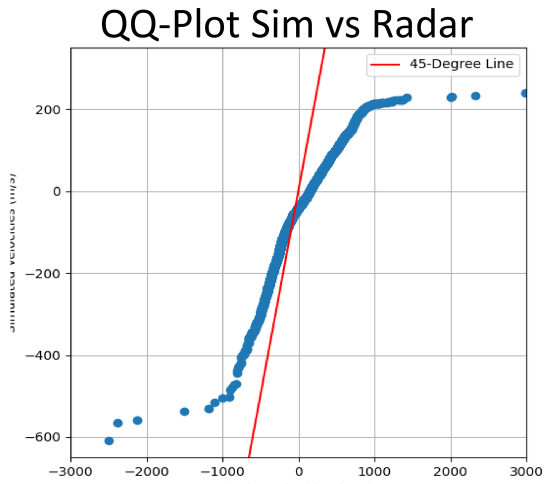
--Range-Time Estimation--



❑ REMIX Shows moderate agreement and appears to capture general convection dynamics; particularly the sign flip around 1300 UT marked w/ green line.

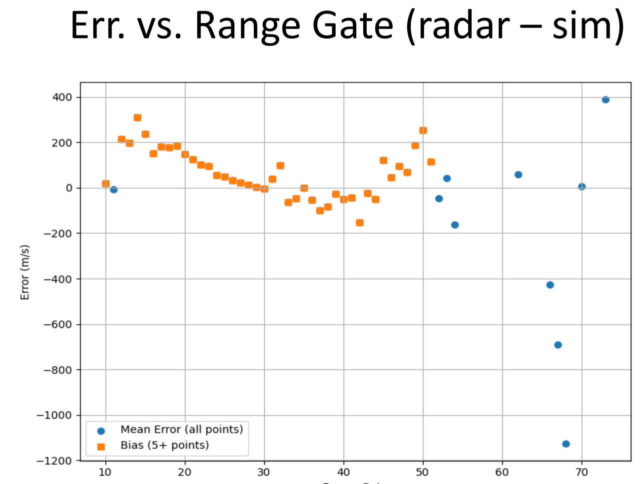
Stat/Metric	Value	Comment
Pearson Correlation:	0.528	Moderate linear relationship.
Best Time-Lagged Correlation:	0.539 at lag -2 steps	Slight improvement by shifting -2min.
Spearman Correlation:	0.573	Better at capturing rank order.
Mean Error (Bias):	75.492 m/s	Simulation underestimates on average.
Mean Absolute Error (MAE):	236.975 m/s	Error is a significant portion of range.
Root Mean Square Error (RMSE):	326.672 m/s	Large errors present.
Outlier Fraction (IQR method):	0.014	Few outliers

QQ-Plot Sim vs Radar



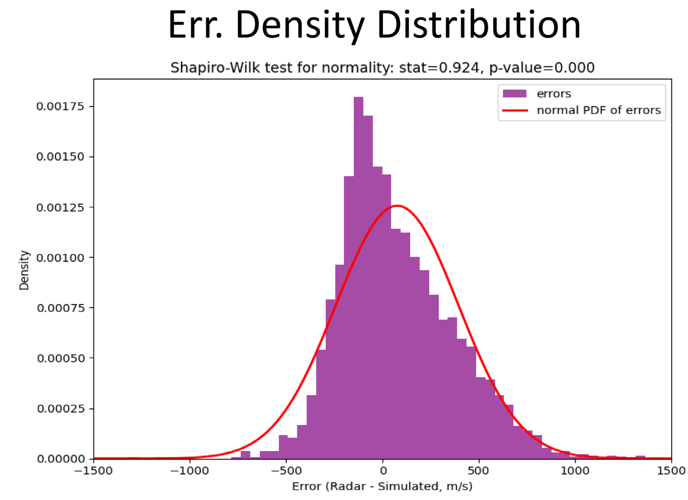
❑ QQ Plot Shows moderate agreement for lower values, but REMIX greatly underestimates.

Err. vs. Range Gate (radar – sim)



❑ Bias Plot Shows largest disagreements due to furthest range gates w/ few points per gate.

Err. Density Distribution



❑ Error Distribution shows somewhat normal, but significant skew; supported by SW test w/ high statistic yet very confident rejection of H₀.

Conclusions

First results from a novel MAGE-SuperDARN comparison tool shows promise for use in IE & MI coupling studies. Simulating the 2015 St. Patrick's day storm through MAGE 0.75 as seen by Adak West revealed:

❑ Moderate overall agreement between REMIX simulation and SuperDARN observations.

- ❑ Qualitatively: Range-time plots show some similar patterns.
- ❑ Quantitatively: Correlation coefficients ~0.5-0.6.

❑ REMIX tends to overestimate electrostatic potential, possibly due to input data, model limitations, or SuperDARN fitting uncertainties.

❑ Our model underestimates extreme velocities, possibly due to simplified B-field model.

❑ Positive bias (75 m/s) indicates our model systematically underestimates velocities on average as well.

❑ Large errors (MAE ~237 m/s, RMSE ~327 m/s) remain significant.

❑ Low velocities tend to be estimated well, but extreme velocities can be missed entirely.

❑ Errors may be range-dependent and exhibit a non-normal distribution.

❑ Slight temporal offset (-2 min) between simulation and observations suggests REMIX performs well out-of-the-box for general spatial-temporal potential distributions.

References

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❑ The Adak West radar has been decommissioned but was maintained and operated by Penn .State.

❑ PyDARN (Martin et al., 2025) was used to aid in the interpretation and manipulation of data.

❑ †Simulation results have been provided by the Community Coordinated Modeling Center (CCMC) at Goddard Space Flight Center through their publicly available simulation services (https://ccmc.gsfc.nasa.gov).

❑ The MAGE model is being developed by the NASA DRIVE Science Center for Geospace Storms (CGS). MAGE 0.75 (Sorathia et al., 2023) couples the GAMERA global MHD model of the magnetosphere (Zhang et al., 2019, Sorathia et al., 2020), the RCM model of the inner magnetosphere (Toffoletto et al., 2003) and the ionospheric electrodynamics model REMIX (Merkin & Lyon, 2010).

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