60th General Meeting
25th & 26th of September 2024
New Orleans, LA

Wellbore Positioning Technical Section

The Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA)

Enhanced Models and Implementations for Minimizing Uncertainty in External Magnetic Fields

Arnaud Chulliat, Manoj Nair, Martin Fillion, Sam Califf

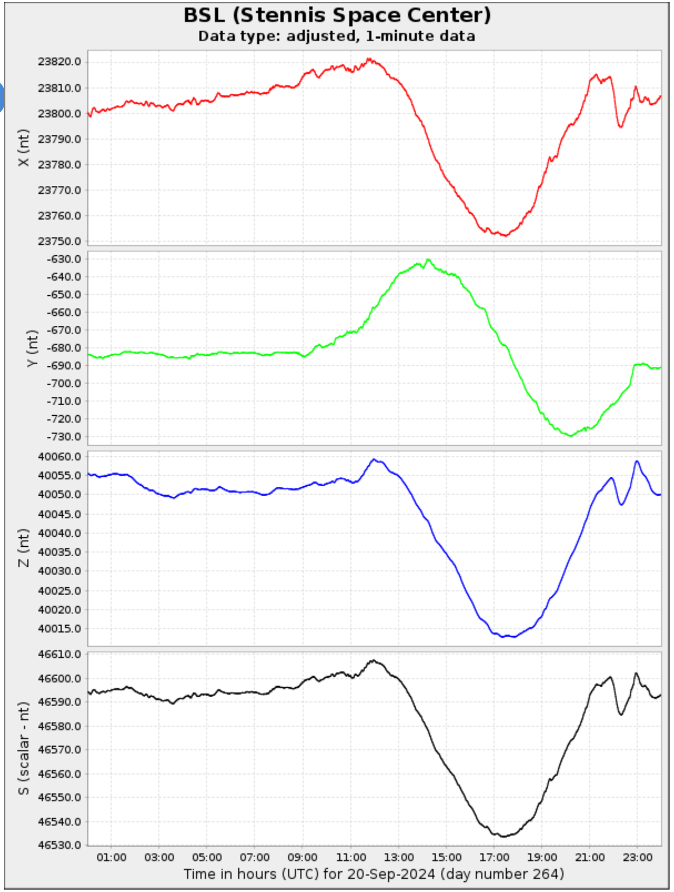
Part 1: Non-Polar Ionospheric Field and Near-Earth Magnetospheric Field Models

Speaker Bio

- Senior Research Scientist with CIRES, University of Colorado Boulder and NOAA National Centers for Environmental Information (NCEI)
- CIRES Lead at NCEI
- Prior experiences: Physicist at Institut de Physique du Globe de Paris, member of INTERMAGNET Executive Council
- Research focus on data-based geomagnetic field modeling and geomagnetic observation systems

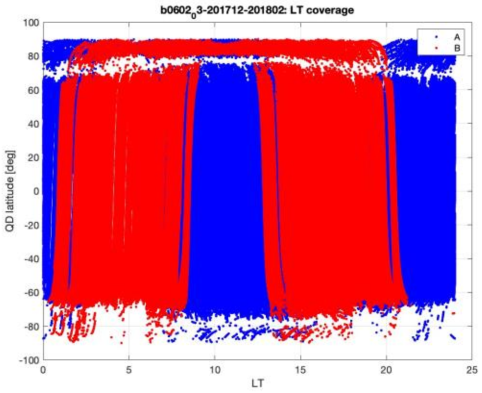
Non-Polar Geomagnetic Daily Variatio

- Present in all geomagnetic field recordings on the ground and in low-Earth orbit (LEO)
- Caused by electric currents in the ionospheric E-region (ionospheric wind dynamo), and induced currents in the Earth's mantle
- Vary by location, season, solar cycle and geomagnetic activity
- Affected by daily fluctuations in thermospheric winds and tides



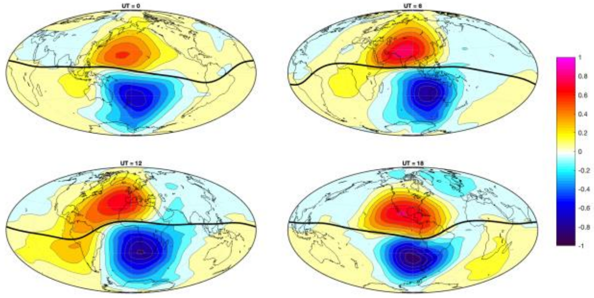
Modeling Methodology

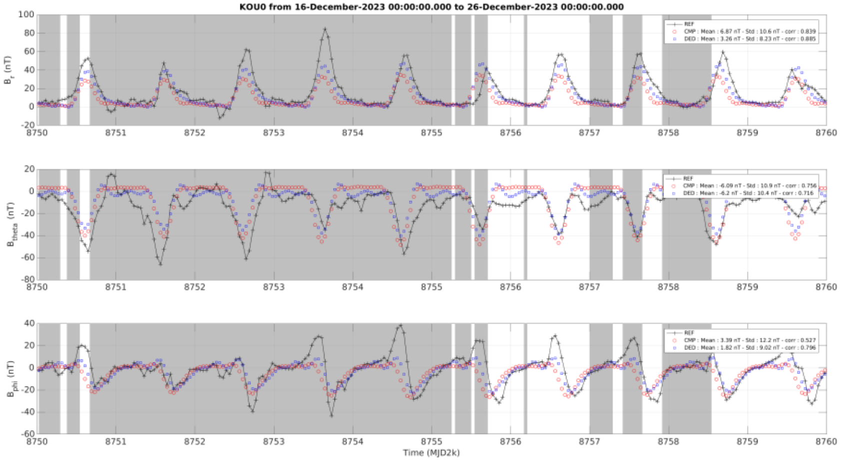
- High-accuracy magnetic field measurements by Swarm satellites in LEO
- Data corrections using advanced core, crustal and external field models
- Data selection during geomagnetically quiet periods and at low and mid quasi-dipole latitudes (< +/- 55 degrees)
- Multivariate regression using spherical harmonics and Fourier series as basis functions
- Separation of primary and induced fields



“DIFI” Model

- Predictions validated against a ground-based magnetic field test dataset
- Regularly updated; DIFI-8 scheduled for release later this year

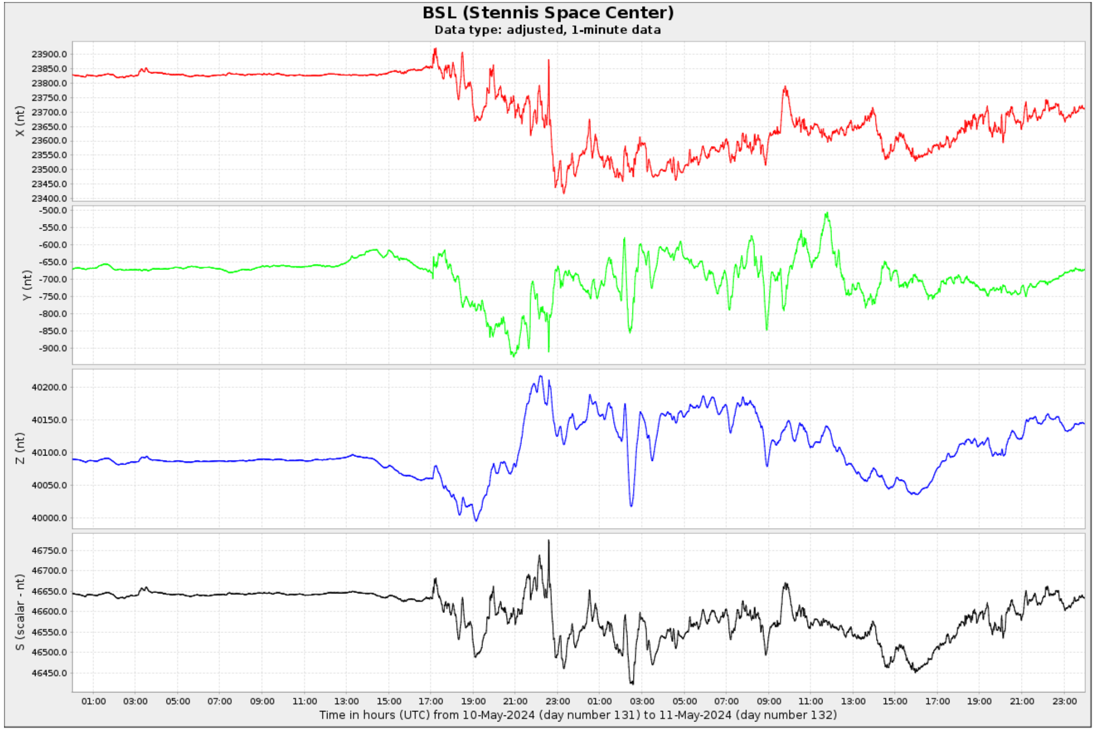




(Chulliat et al., 2024)

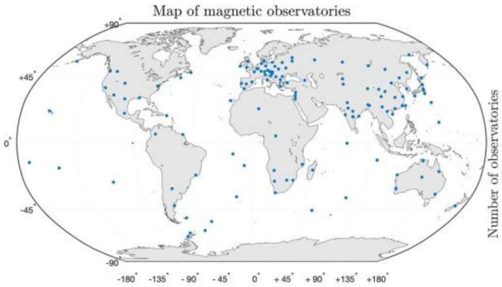
Near-Earth Magnetospheric Field

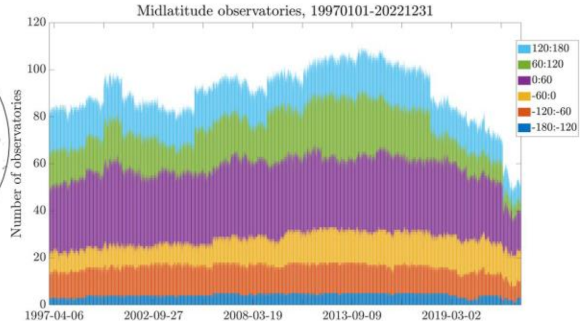
- Main geomagnetic storm signature at low and mid-latitudes; always present
- Caused by magnetospheric ring current and induced currents in the Earth's mantle
- Significant variations with longitude and local time

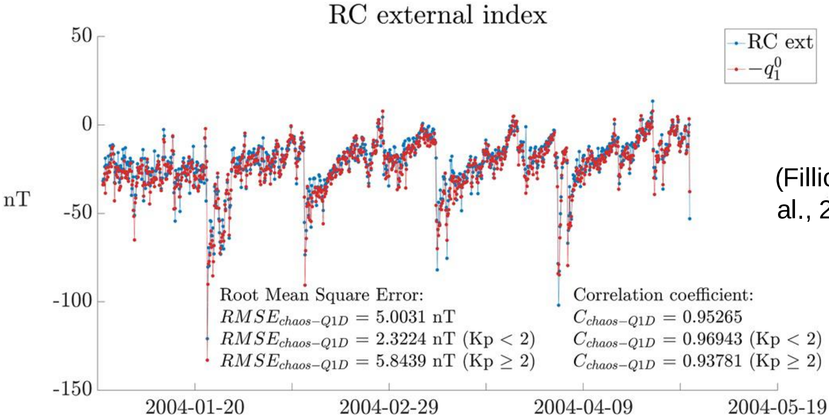


Modeling Methodology

- Ground-based observatory measurements (H component)
- Data corrections using advanced core, crustal, and external field models
- Data selection at mid quasi-dipole latitudes (excluding poleward of +/- 55 deg and equatorward of +/- 5 deg)
- Degree and order 2 spherical harmonics representation
- Separation of primary and induced fields



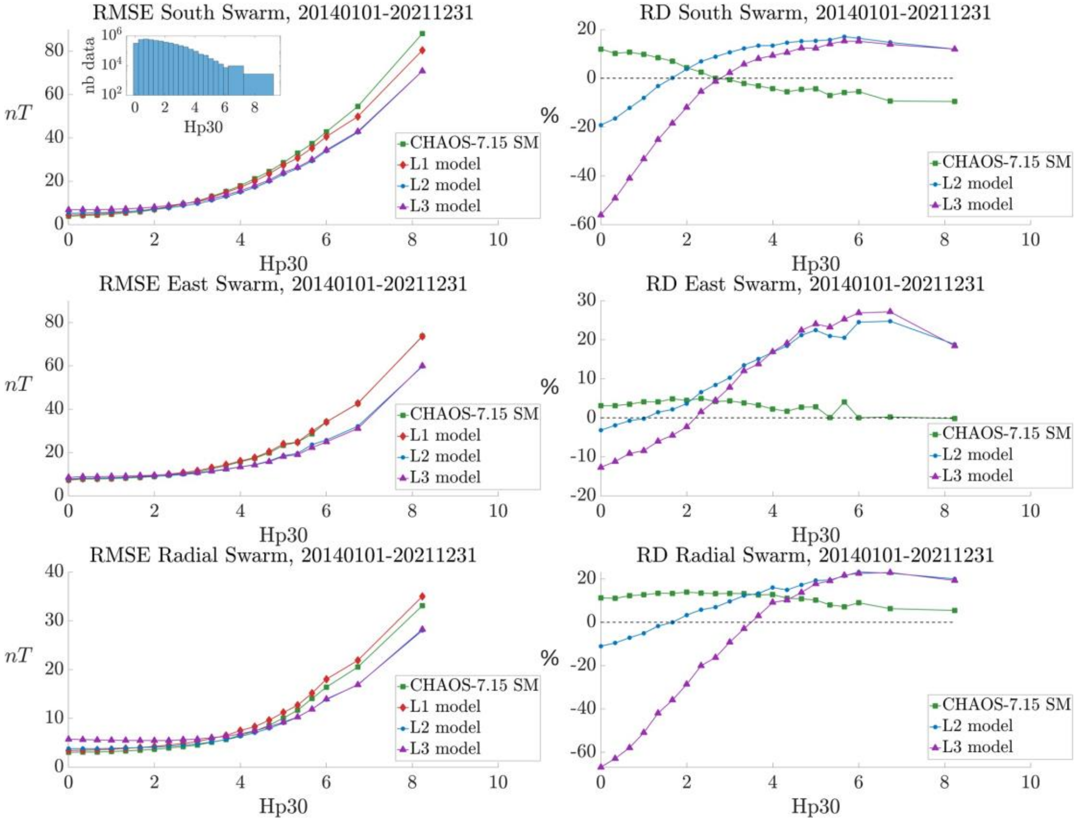




(Fillion et al., 2024)

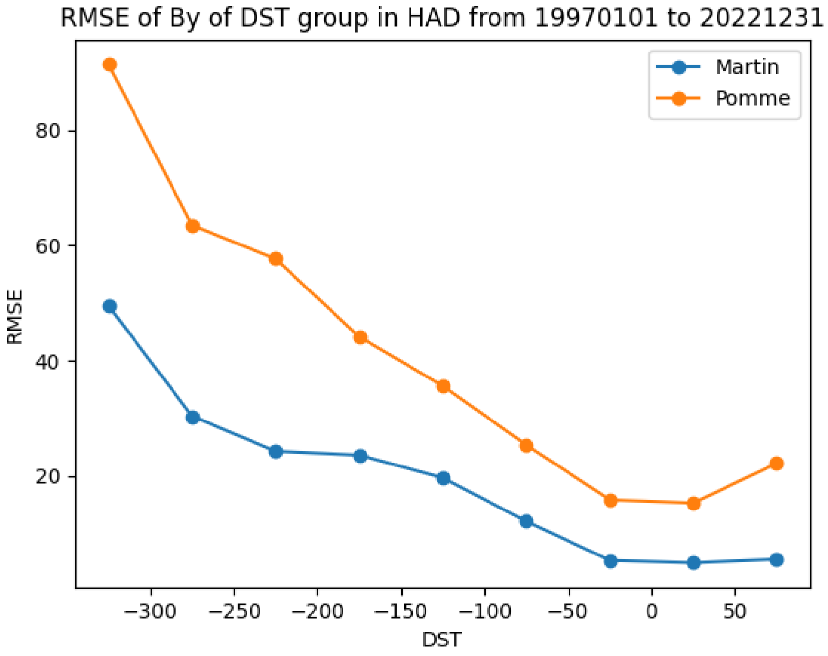
Model Performance (1)

- Comparison with Swarm, CHAMP, and Oersted satellite data
- Degree 2 model improves fit to satellite data during moderate and high geomagnetic activity levels



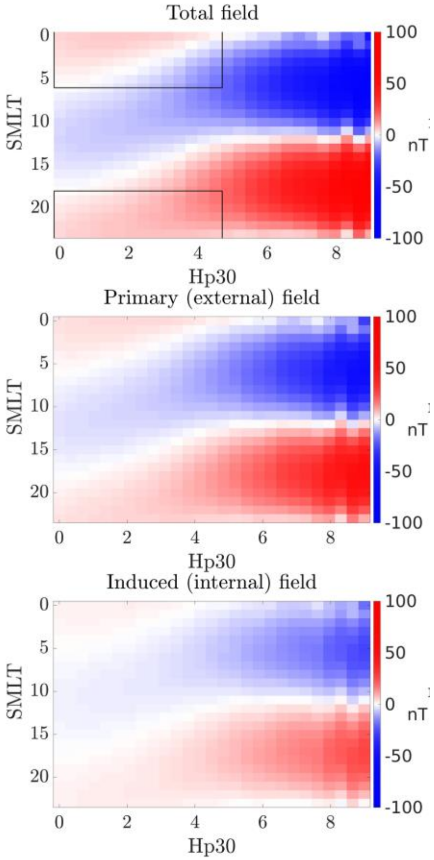
Model Performance (2)

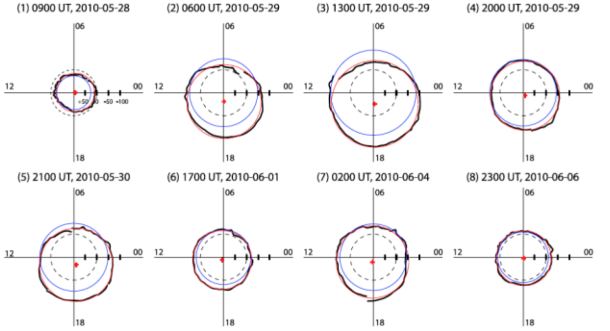
- K-fold validation using ground-based observatories
- Degree 2 models improve fit to ground-based data in most locations



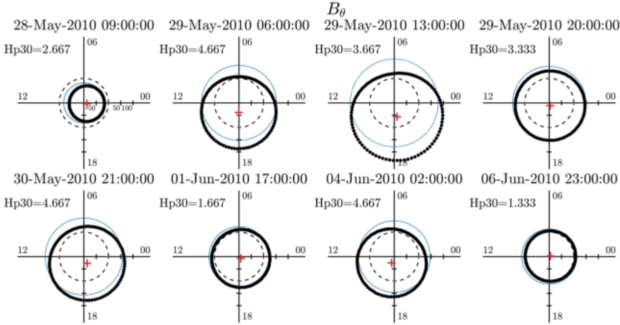
Local Time Asymmetry

- Significant dawn-dusk asymmetry for moderate and high geomagnetic activity (averaged over 25 years)
- Amplitude of the asymmetry increases with activity
- Model able to independently reproduce results obtained with data from the C/NOFS satellite for the geomagnetic storms on 22 July 2009 and 29 May 2010





(Le et al., 2011)



(Fillion et al., 2024)

Part 2: High-Latitude Disturbance Field Model

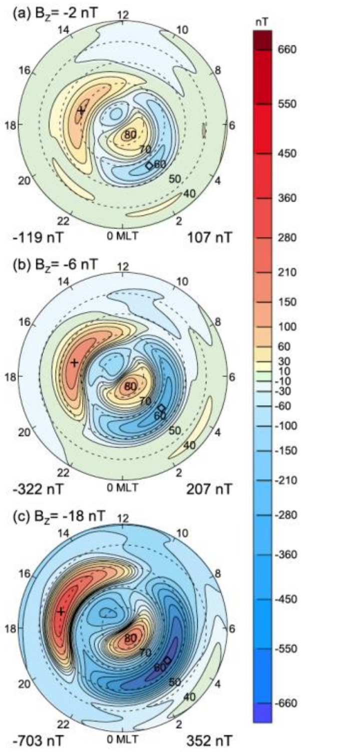
Speaker Bio

- Manoj Nair
  - Lead of Research, Geomagnetism
  - **CIRES, University of Colorado and US National Oceanic and Atmospheric Administration**
  - 20+ years research experience in geomagnetism
  - PhD in Geophysics
  - Boulder, CO
  - Specialized in
    - Geomagnetism
      - Modeling, Signal-processing, Machine-learning

- High-latitude regions experience significant uncertainty in magnetic referencing due to magnetic disturbances from the ionosphere and magnetosphere.
- The accuracy of geomagnetic observatory data (IFR-2) declines as the distance from the drill site to the observatory increases.
- Establishing and operating magnetic reference observatories in offshore regions is inherently challenging.
- The Weimer Geomagnetic Perturbation Model (WGPM) provides an empirical model of magnetic field variations in high-latitude regions (>55°).
- How effectively does the WGPM capture these high-latitude variations? Can it help reduce space-weather-induced noise in MWD (Measurement While Drilling) data?

Weimer geomagnetic perturbation model (WGPM)

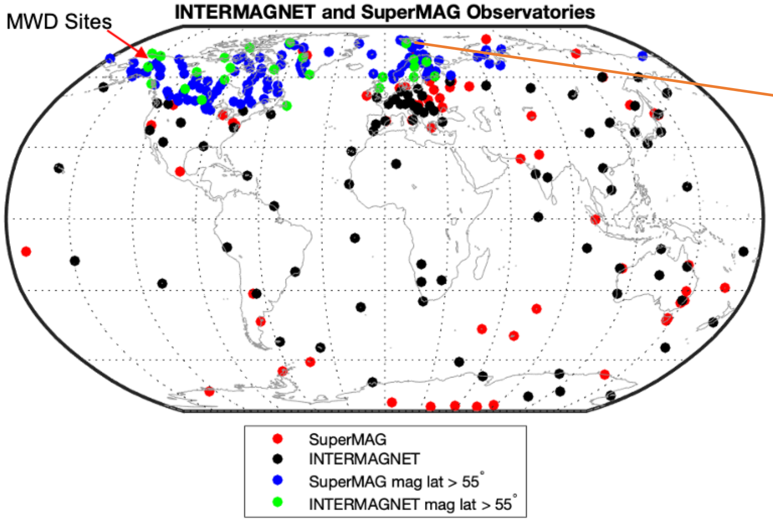
- Empirical model of high-latitude magnetic perturbations
  - Spherical cap harmonics
- Derived using 8 years of ground observatory data in the northern hemisphere
- Solar wind data are used as inputs
  - 5 min averages, then averaged to 25 minutes with a 45-minute delay to account for propagation delays



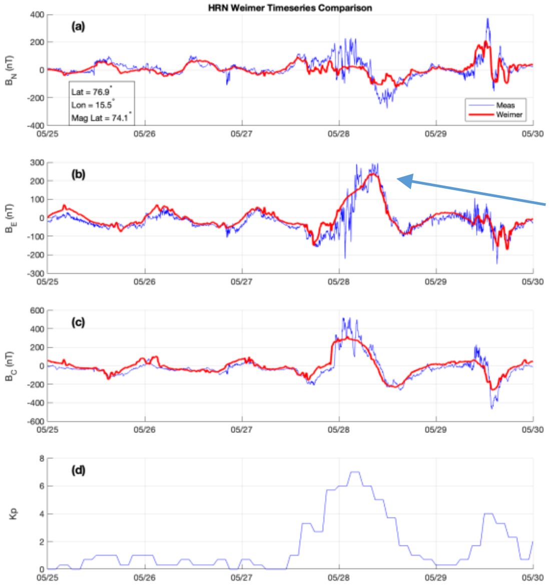
[Weimer, 2013]

Figure 2. Maps of ΔB_{North} for southward IMF at three magnitudes. (a) IMF $B_Z = -2$ nT, (b) IMF $B_Z = -6$ nT, and (c) IMF $B_Z = -18$ nT.

Observatory sites used to validate the WGPM model



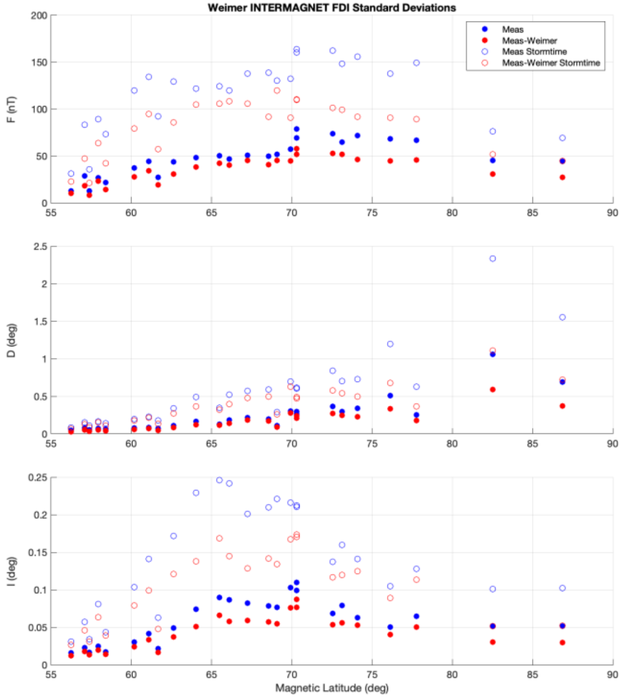
Hornsund observatory, Norway



Systematic magnetic disturbances lasting for more than 12 hours

From S. Califf, M. Nair, D. Weimer, N. Zachman, and B. Poedjono, Paper *Under Review with Space Weather, 2024*

Standard deviations of the total field (F), declination (D) and inclination (I) errors based on the measurements (blue) and measurement with WGPM subtracted (red) as a function of magnetic latitude. Results for all of the data are plotted in closed circles, and open circles represent data for Kp >= 4.

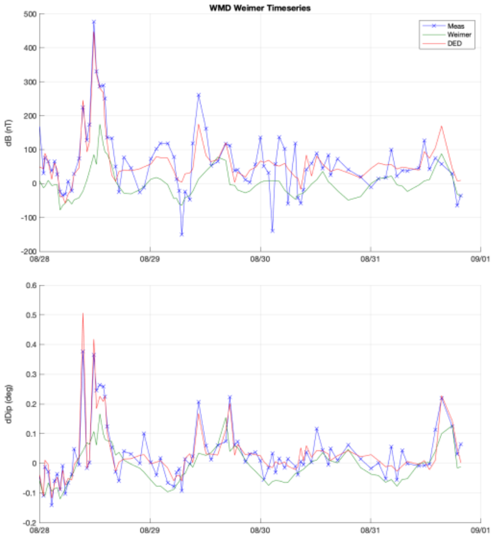


Califf et al., *Under Review with Space Weather, 2024*

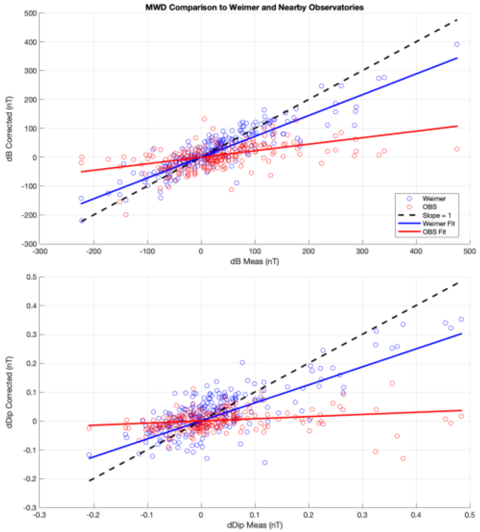
All Data						
Std. Dev.	HRGM Baseline	Measured Disturbance	WPGM Compensated	HRGM + Measured Disturbance RSS	HRGM + WPGM Compensated RSS	% Difference
Total Field (nT)	107	47.67	35.67	117.14	112.79	3.7
Declination (deg)	0.3	0.242	0.170	0.385	0.345	10.5
Inclination (deg)	0.16	0.059	0.044	0.170	0.166	2.7
Kp >= 4						
Total Field (nT)	107	116.66	81.21	158.30	134.33	15.1
Declination (deg)	0.3	0.573	0.390	0.647	0.492	23.9
Inclination (deg)	0.16	0.144	0.103	0.215	0.191	11.4

*HRGM – High Resolution Geomagnetic Model

Variations in total field (top panel) and inclination (bottom panel) from MWD data (blue line) compared to WGPM (green line) and Deadhorse observatory (DED) (red line).

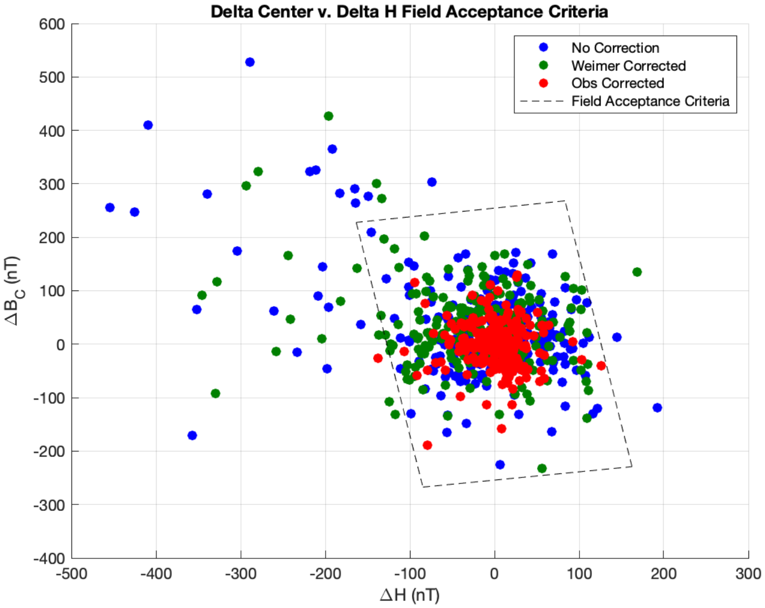


Variations in total field (top panel) and inclination (bottom panel). Compensated measurements are plotted against uncompensated measurements using WGPM (blue) and nearby observatories (red).



Califf et al., *Under Review with Space Weather, 2024*

The difference in the Horizontal ($\sqrt{E^2 + N^2}$) and Center magnetic field components between downhole MWD measurements and indicated geomagnetic reference models. A station with a value (0,0) indicates that the MWD measured the magnetic field exactly as described by the geomagnetic model.



Califf et al., *Under Review with Space Weather, 2024*

Part-2 Conclusions

1. WGPM reduces errors in magnetic declination by an average of 23.9% during the geomagnetic storms (Kp >=4), indicating its potential to improve real-time magnetic field estimates where direct measurements are unavailable.

2. WGPM also demonstrates its practical application in reducing the effects of geomagnetic disturbances on MWD data from high-latitude drilling operations, making it a useful tool in areas without real-time observatory data.

Geomagnetic Storms and Diurnal Variations

Geomagnetic storms and diurnal variations can induce significant, prolonged deviations in the Earth's magnetic field, lasting several hours or more.

Correlated Errors in MWD Measurements

A part of the disturbance-induced errors in MWD data may exhibit correlation between consecutive measurements, complicating interpretation.

Model-Based Corrections

In the absence of nearby observatory data, applying model-based corrections for magnetic disturbances can improve magnetic referencing.