# Development of a low-cost magnetometer system for a coordinated space weather monitoring

**Hyomin Kim**, New Jersey Institute of Technology

Nathaniel Frisell, University of Scranton

Rachel Frissell, University of Scranton

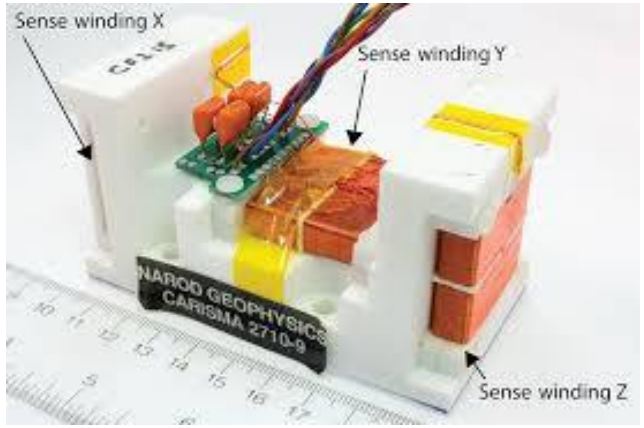
David Witten, HamSCI Community

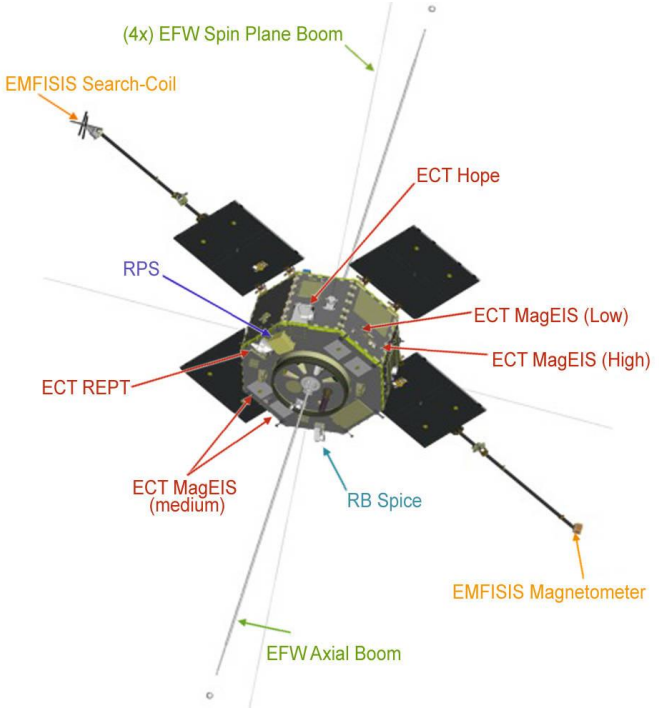
Daniel Clancy, New Jersey Institute of Technology

**Acknowledgement:** The work at the University of Scranton and New Jersey Institute of Technology was supported by the National Science Foundation under grants AGS-2432821 and AGS-2432823, respectively. The authors would like to thank the HamSCI members for development and installation of the instrument, and provision of data.

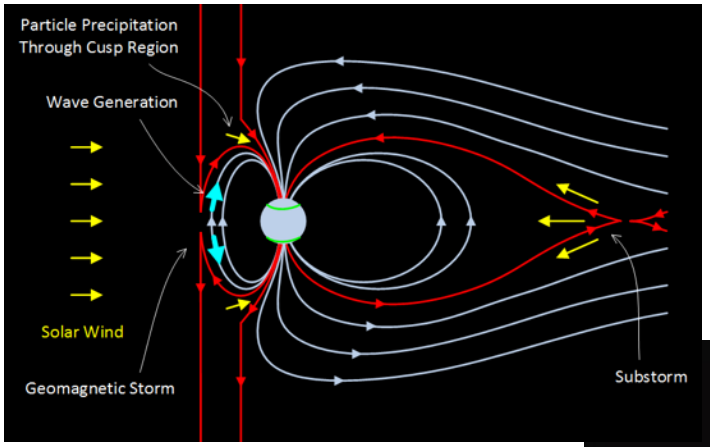
# Magnetometer

- Magnetometer is one of the critical instruments for space science studies.
- Measures **B** and/or d**B**/dt (vector and scalar).
- Wide application: metal detection, non-contact switch, non-destructive testing, oil/coal exploration, military, space research, etc.

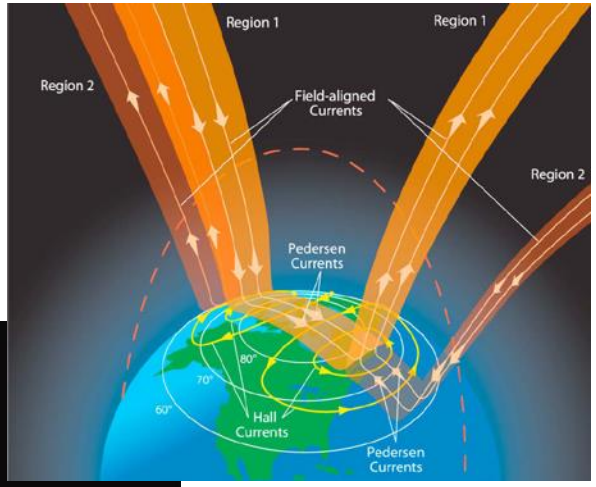


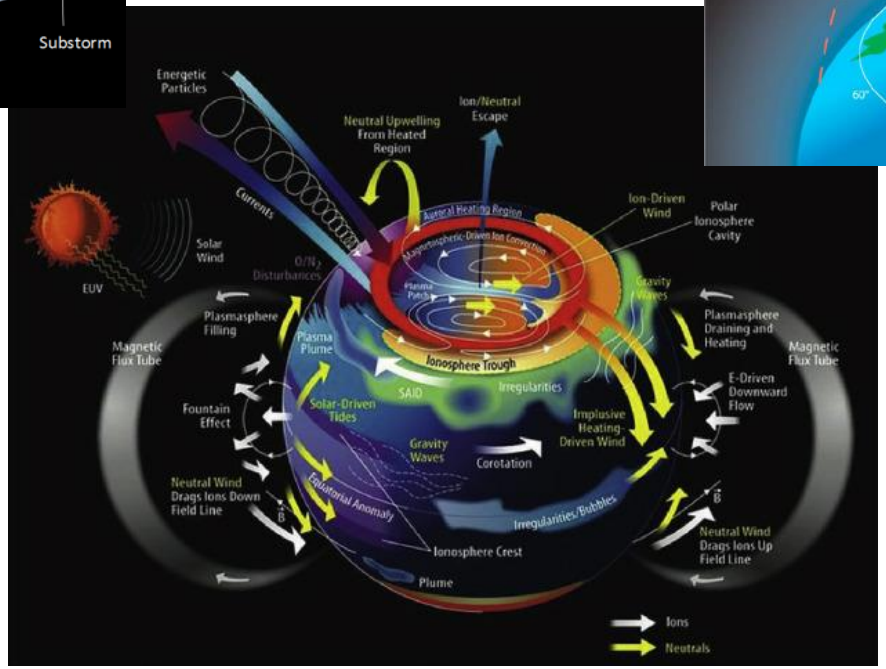
# Magnetometers for Geospace Sciences




The Sun and the Earth are connected via magnetic fields.



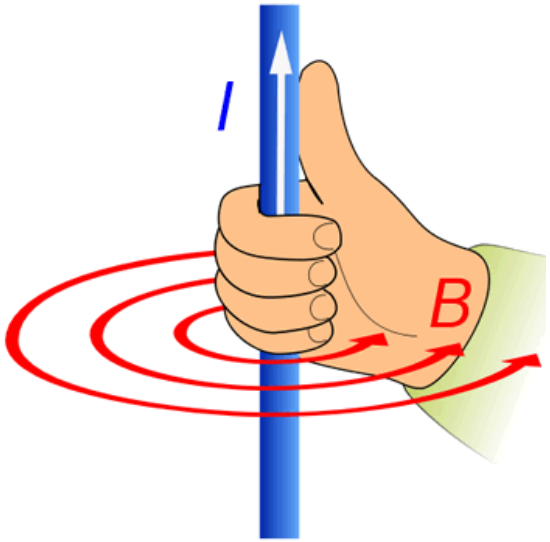

The Sun-Earth connection creates a unique geomagnetic field structure: The **Earth's Magnetosphere.**




Geospace environments and space weather are affected by a variety of the ***current systems*** in the magnetosphere and ionosphere due to the coupling between the Sun and the Earth → ***energy transfer*** from the Sun to the Earth.

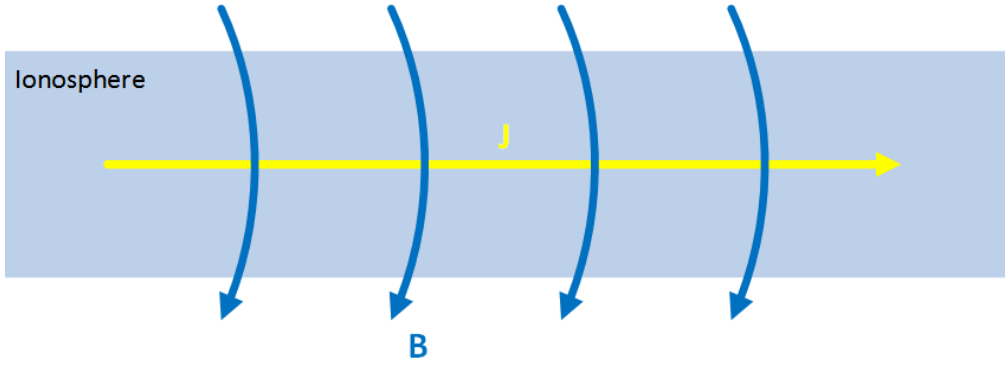
# Magnetic Field Measurement on the Ground

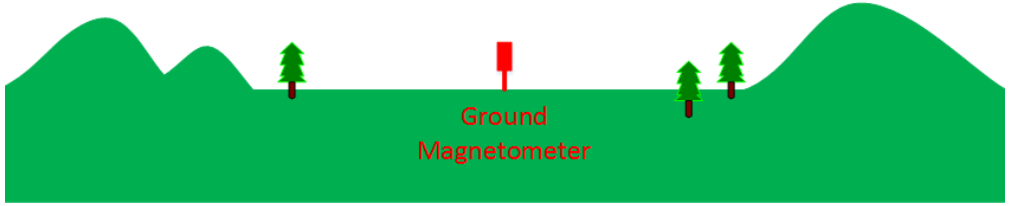
Electric currents produce magnetic fields around the loop that carries the currents.

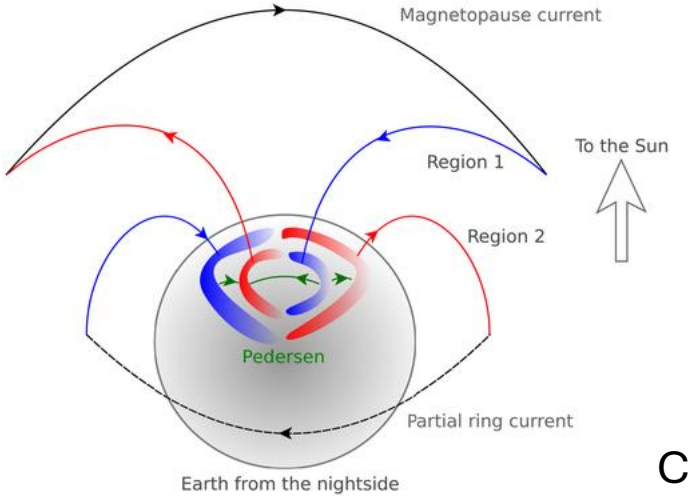



Ampere's Circuital Law

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$



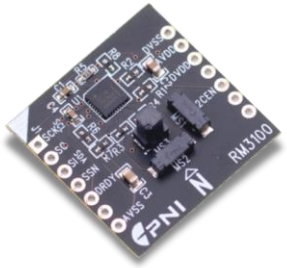



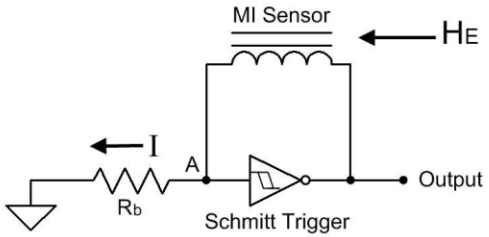

Carter et al. 2016

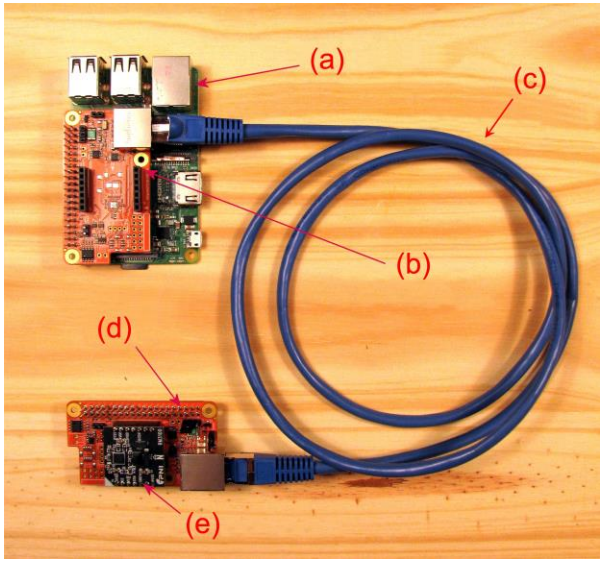
# Project Goals: HamSCI Magnetometer Network

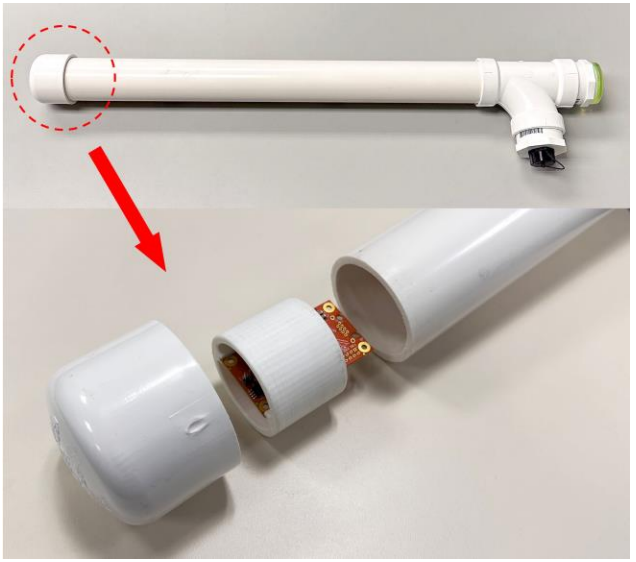
- To establish a low-cost, densely-spaced magnetic field sensor network to provide quantitative and qualitative measurements of the geospace environment from the ground.
- Target performance level: < ~5 nT field resolution at 1-sec sample rate (note: Earth's magnetic field ranges from 25,000 to 65,000 nT).
- Time-varying field measurement is sufficient: absolute measurement is not necessary.
- Magnetometer data will be combined with HF radio observations to monitor large-scale current systems and ionospheric disturbances.

# HamSCI Magnetometer

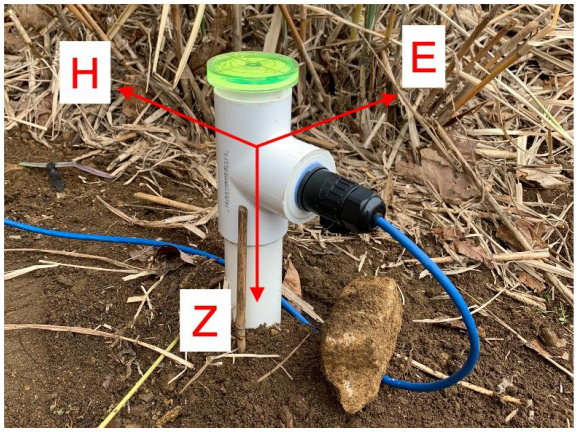


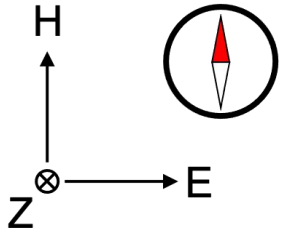



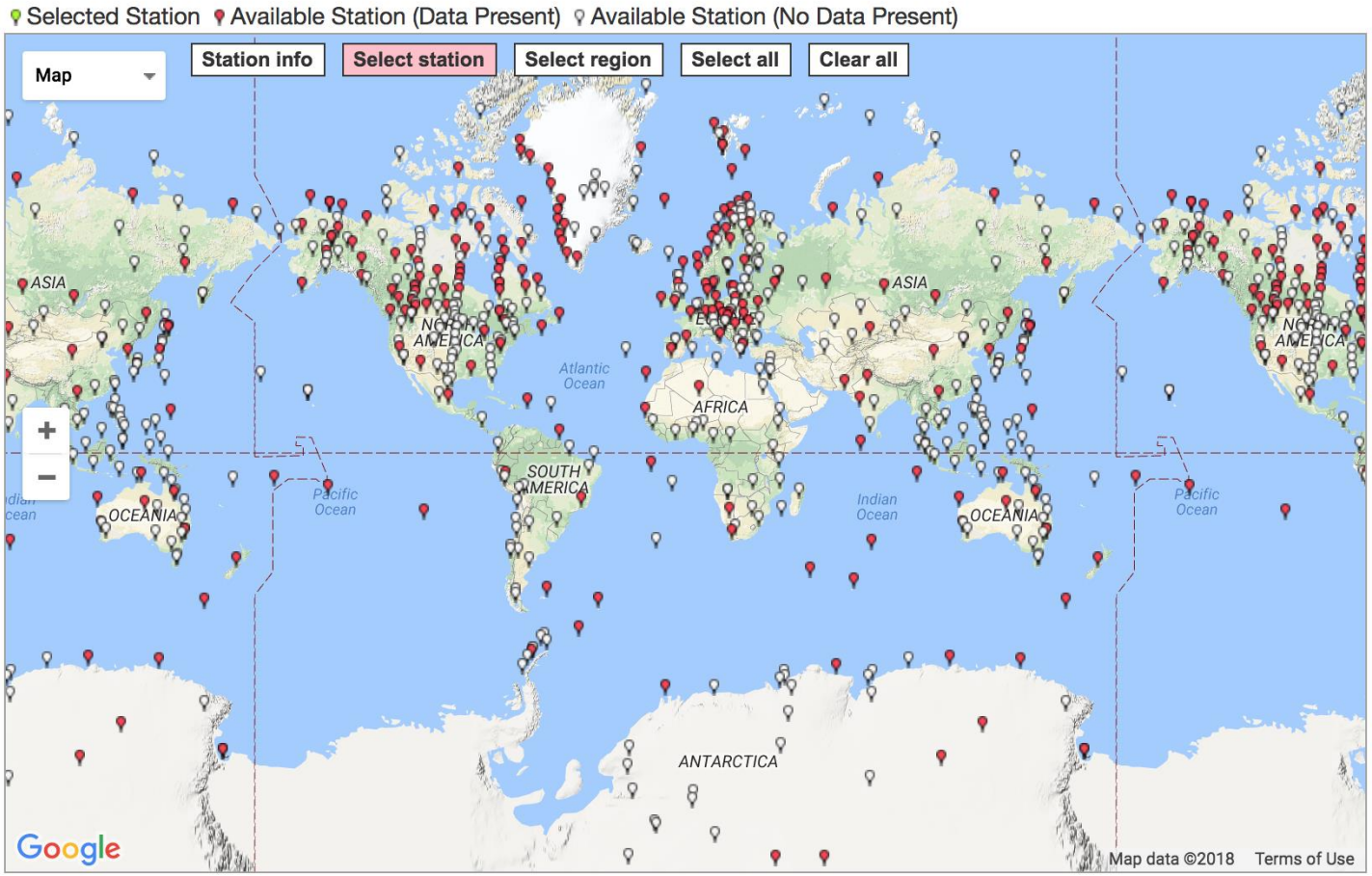
- PNI RM3100 magneto-inductive sensor (pnicorp.com)
- Low power, low mass, small size and large dynamic range (±1100 $\mu$T)
- High resolution: ~on the order of 5 nT
- Tri-axial measurements
- I2C and SPI interfaces
- Sampling rate: 1 sample/sec
- $25 (sensor only)



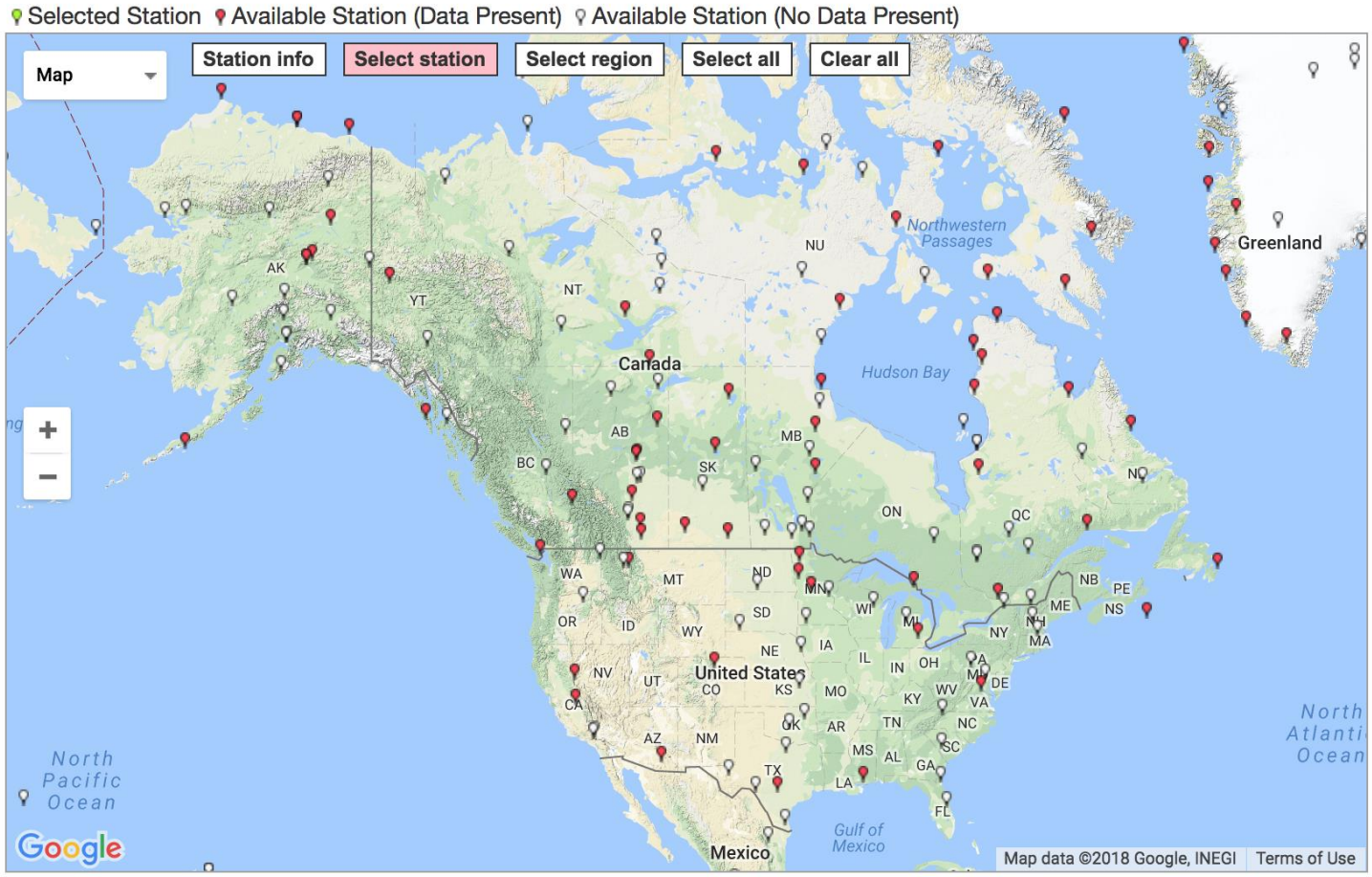

*Demo: D1, R. Frissell et al., "Understanding HamSCI Magnetometer Measurements and Observations"*

# Example of Magnetometer Network: SuperMAG




Run by JHU/APL, Funded by NSF.

# Example of Magnetometer Network: SuperMAG

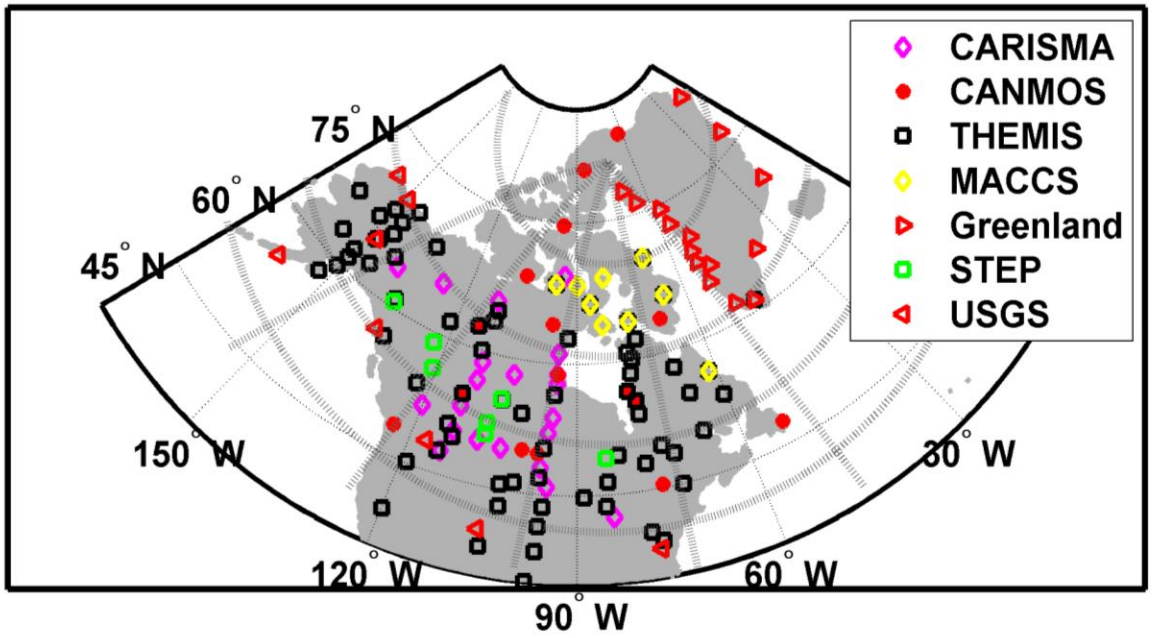



Run by JHU/APL, Funded by NSF.

# Science Example: Ionospheric Currents

- ***Ionospheric current systems*** derived from ground-based magnetometer data [e.g., Amm and Viljanen, 1999; Weygand et al., 2011].
- Provides context for All Sky Images, Ionospheric Radars, MI coupling, and Riometers.
- Magnetometer coverage has changed significantly over the years.
  - Number of stations in the lower 48 states is now about ~10 down from about 24.
  - Number of stations in Eastern Canada has increased.
- In order to meets the requirements of the Space Weather Action Plan the number of stations in the lower 48 needs to increase to diagnose the possible dB/dt spikes.

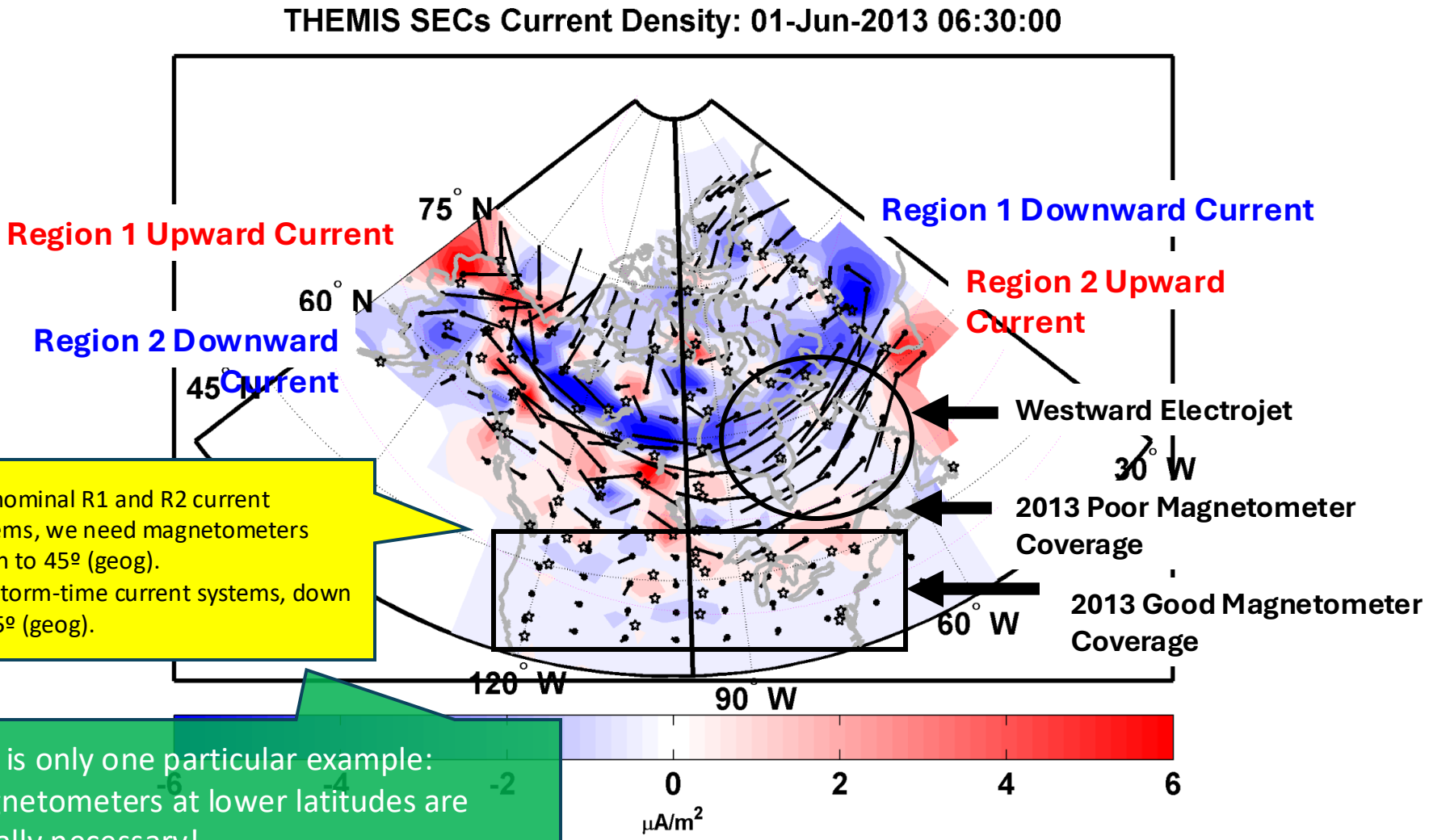
**CARISMA, CANMOS, GIMA, Greenland, MACCS, McMAC, THEMIS, STEP, USGS**




Ionospheric currents are estimated using Ampere's Law.

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{encl}}$$

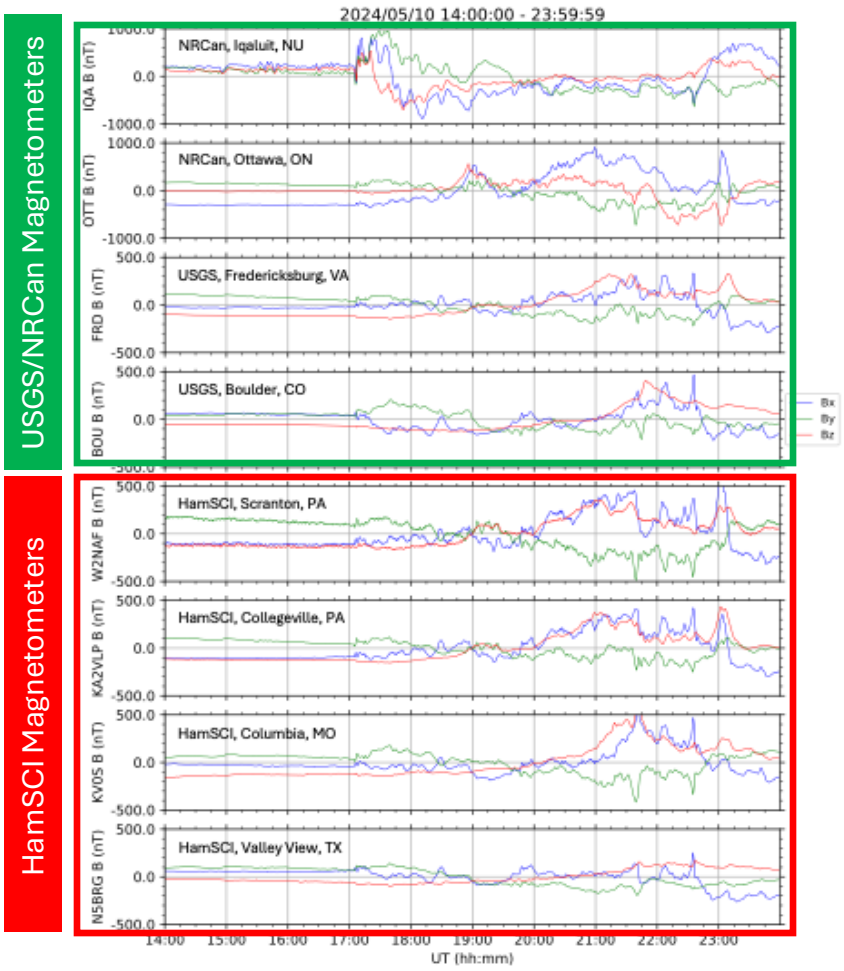
# Science Example: Ionospheric Currents During 2013/06/01 Storm



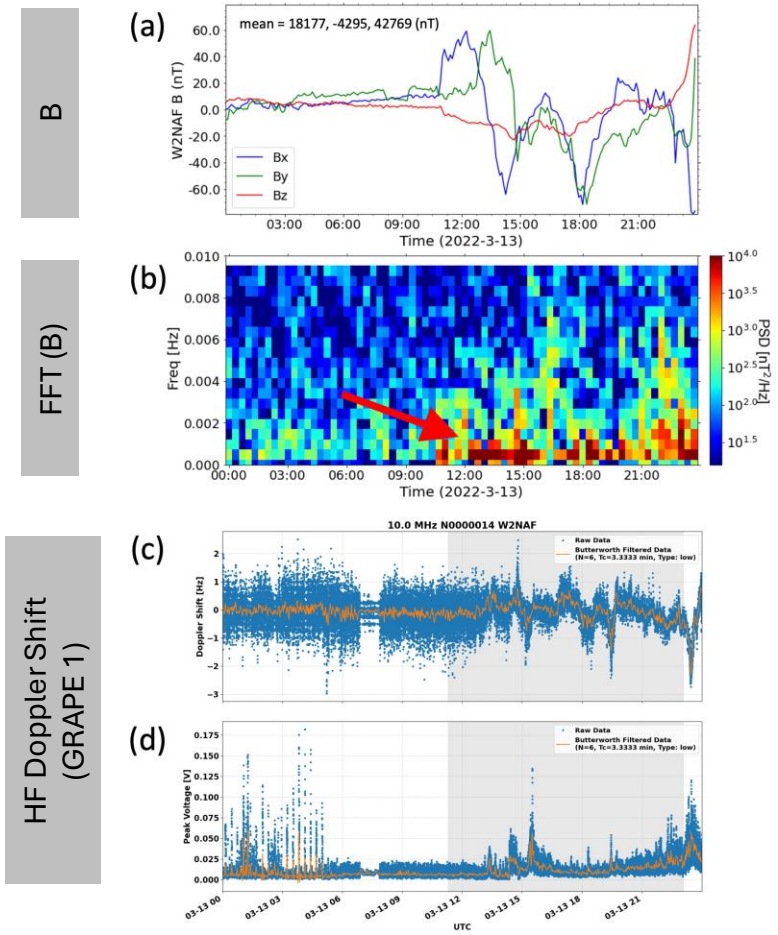

- For nominal R1 and R2 current systems, we need magnetometers down to 45º (geog).
- For storm-time current systems, down to 35º (geog).

This is only one particular example: magnetometers at lower latitudes are equally necessary!

# HamSCI Magnetometer Network



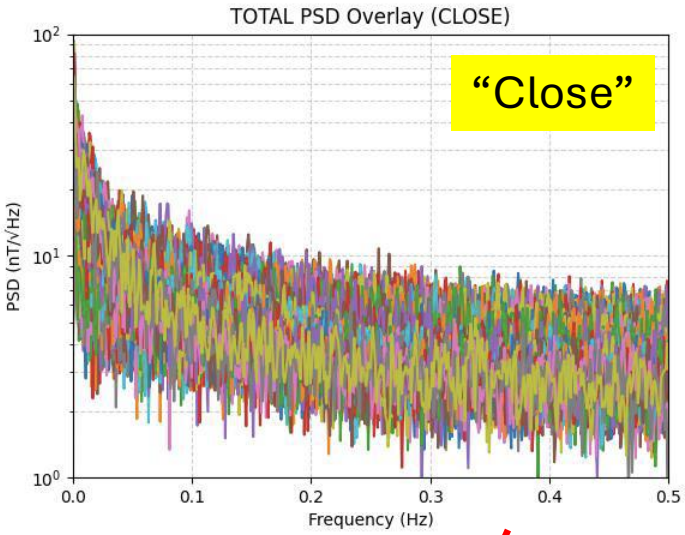

Magnetometer data acquired during the geomagnetic storm on May 10, 2024.

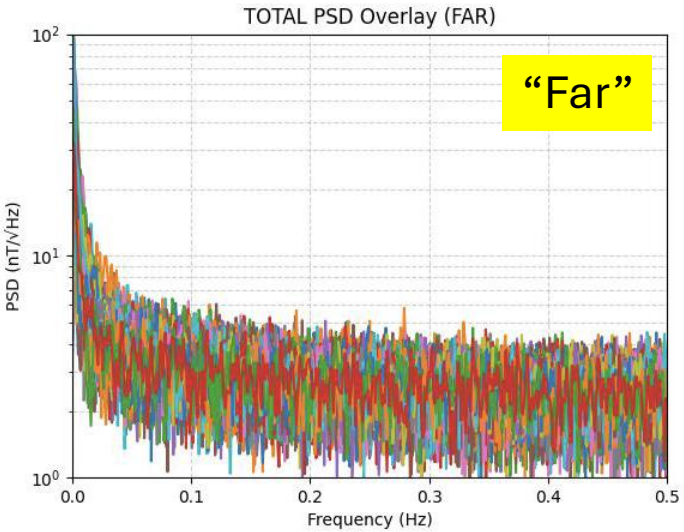



HamSCI PSWS magnetometer and GRAPE 1 data acquired during the geomagnetic storm on March 13, 2022.

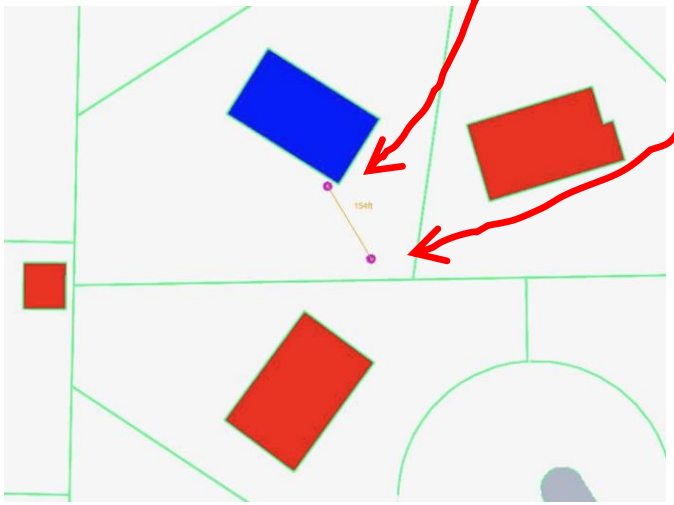
from *Kim et al. [2024]*

# HamSCI Magnetometer: Noise Analysis



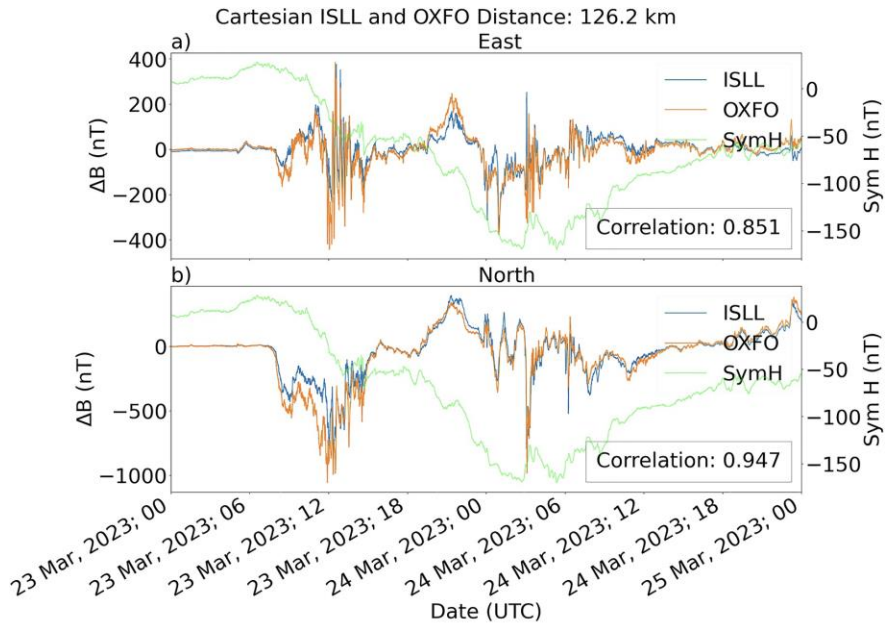



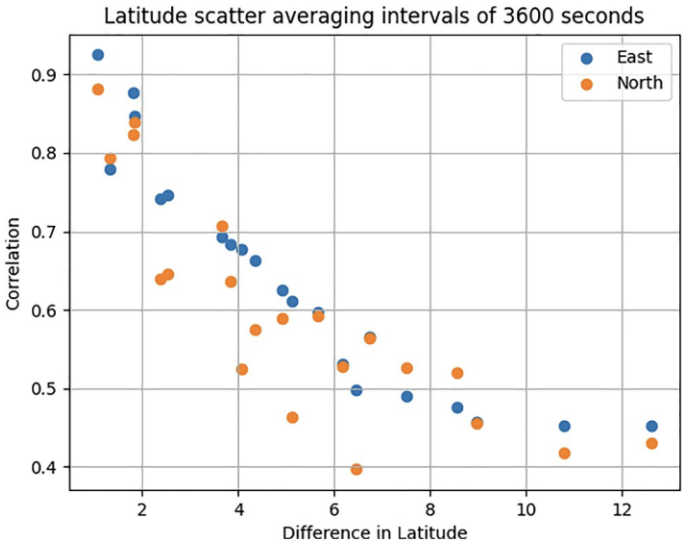

*Poster presentation (P26): D. Clancy et al. "Assessment of a Low-Cost Magneto-Inductive Magnetometer for Personal Space Weather Stations"*



- HamSCI magnetometer measurements for 1 week at two locations in a suburban residential area ("close" vs "far").
- Each color represents a 1-day measurement.
- A clear reduction in noise when the sensor is placed far from the house: Noise floor @ 0.1 Hz: 3.23 nT/$\sqrt{\text{Hz}}$ vs 5.74 nT/$\sqrt{\text{Hz}}$.

# Spacing of Magnetometers for Identification of Ionospheric Small-Scale Currents




- The conventional wisdom for ground magnetometer station separation is based on outdated assumptions.
- Current magnetometer arrays do not sufficiently measure small-scale geomagnetic disturbances.
- Recommendation for spacing of future ground magnetometers in the auroral zone is ***100–150 km***.

Correlations calculated between pairs of stations in the CARISMA Churchill meridional (N-S) line averaging 1 hr intervals from 7 to 8 September 2017.

1° latitude ≈ 110 km N-S separation.

*From "Identifying Ionospheric Small-Scale Currents: A Spatial Correlation Study Using Closely-Spaced Pairs of Ground Magnetometers", Gottesman et al. [2024].*

# Summary

- A low-cost, magneto-inductive type magnetometer for the HamSCI PSWS project are presented.
- The performance of the HamSCI magnetometer is comparable to that of professional, science-grade magnetometers for observations of large-scale geospace events such as geomagnetic storms and substorms.
- Current magnetometer arrays do not sufficiently measure small-scale geomagnetic disturbances.
- HamSCI proposes a closely-spaced (100-150 km) magnetometer network for small-scale ionospheric currents.