HamSCI Magnetometer Network for Space Weather Monitoring

Hyomin Kim, KD2MCR

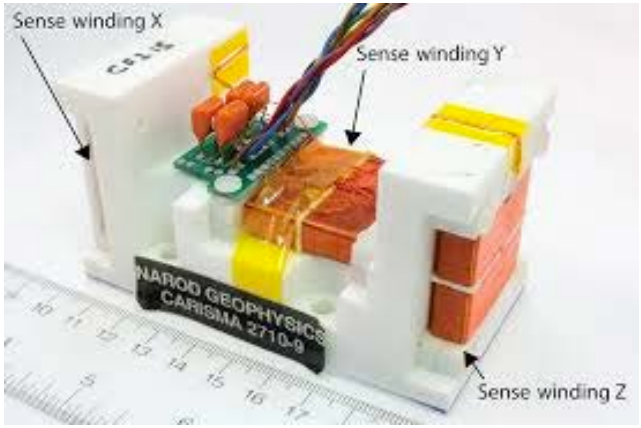
Nathaniel Frissell, W2NAF

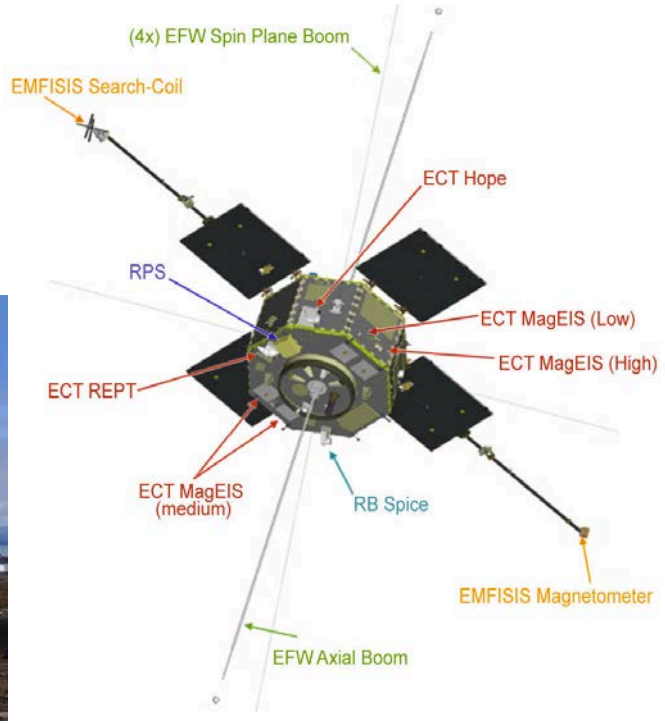
New Jersey Institute of Technology (NJIT)
Center for Solar-Terrestrial Research (CSTR)

Thanks to: NJIT Undergraduate Students, Troy Asare, Baladithya Balamurugan, Jonpierre Grajales, Kush Sheth

Magnetometer

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





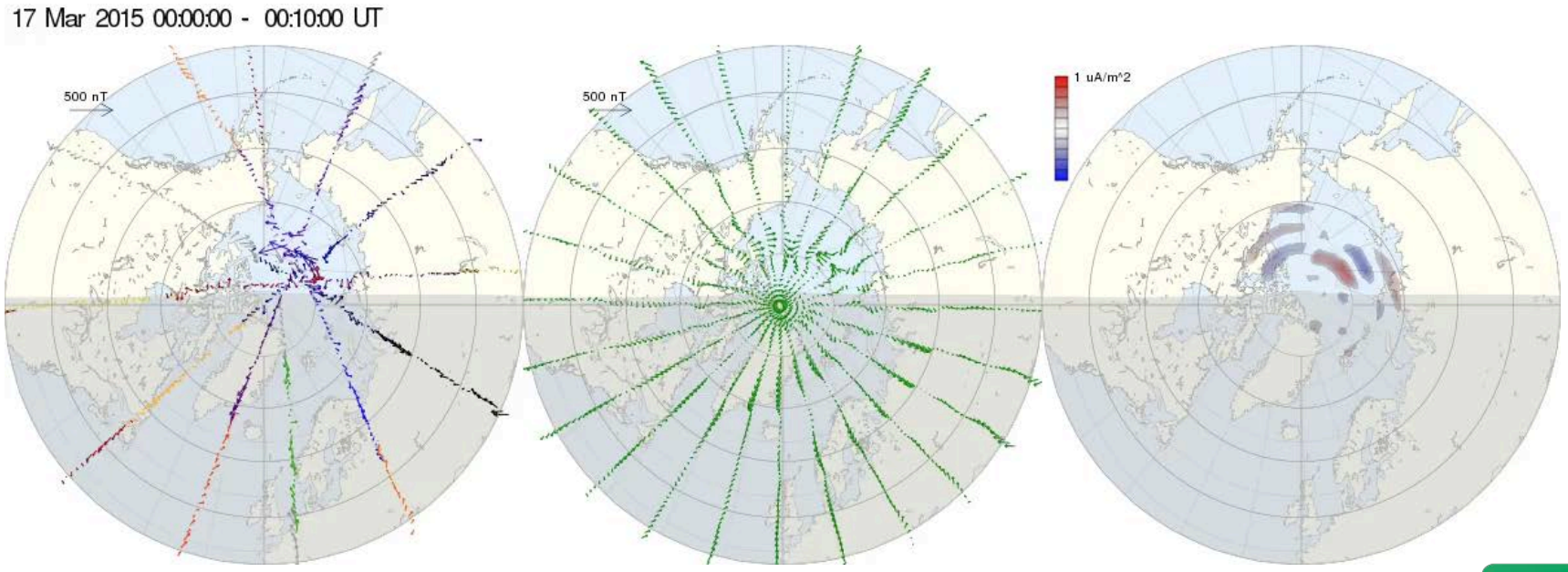
Project Goals: HamSCI Magnetometer Network

- To establish a densely-spaced magnetic field sensor network to observe Earth's magnetic field variations.
- Target performance level: ~10 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.

Why Magnetometer?

- Magnetometer is one of the critical instruments for space weather research.
- Data acquisition/handling is relatively straightforward (especially for ground-based observations).
- Affordable off-the-shelf options are available.
- Relatively simple, in-house design/fabrication is also possible.
- Great opportunity for citizen scientists and space science/weather community.

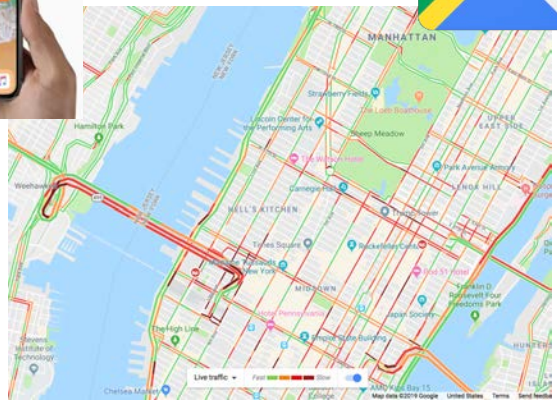
Why We Do This?



Active Magnetosphere and Planetary Electrodynamics Response Experiment

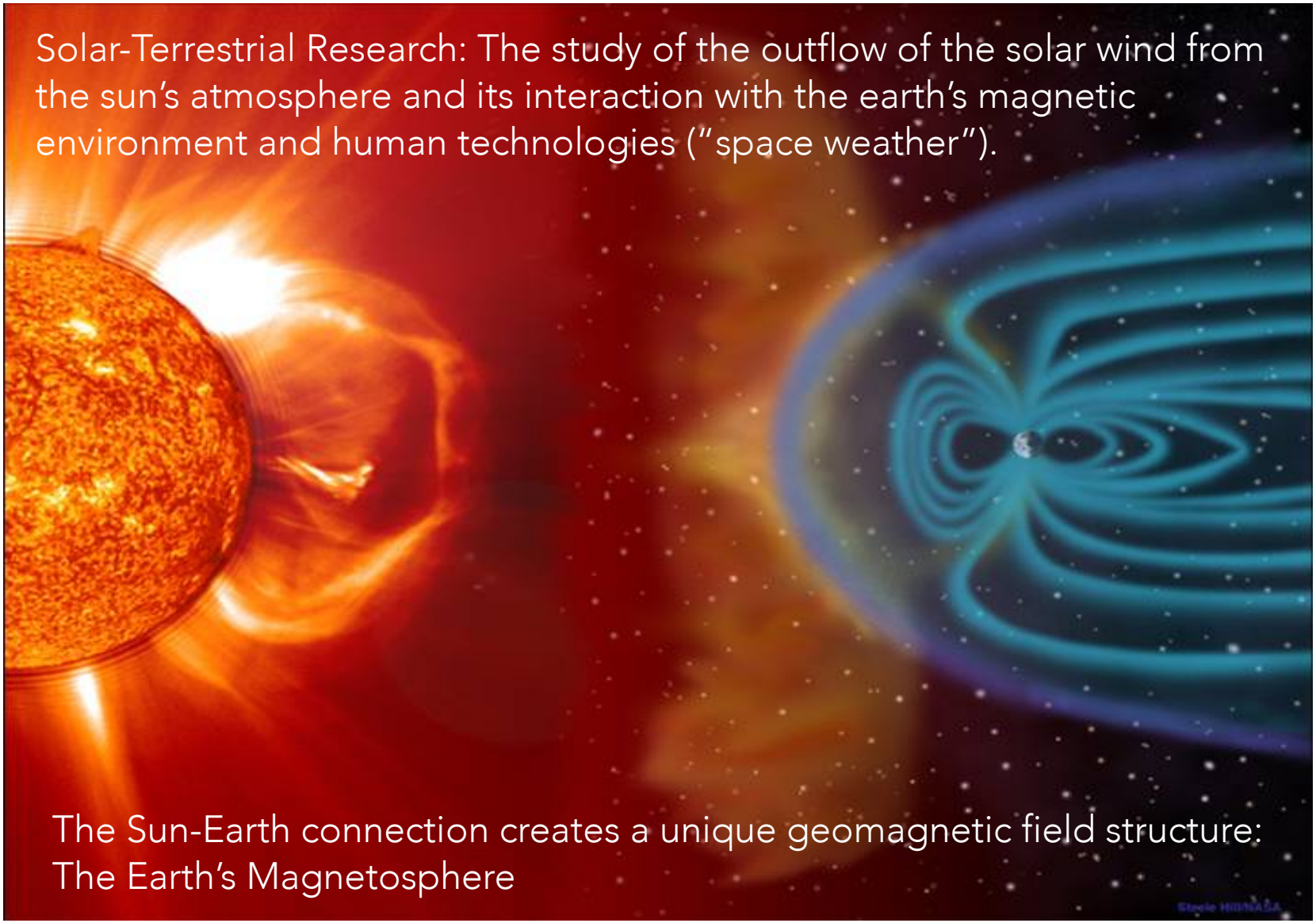
AMPERE

APL iridium BOEING

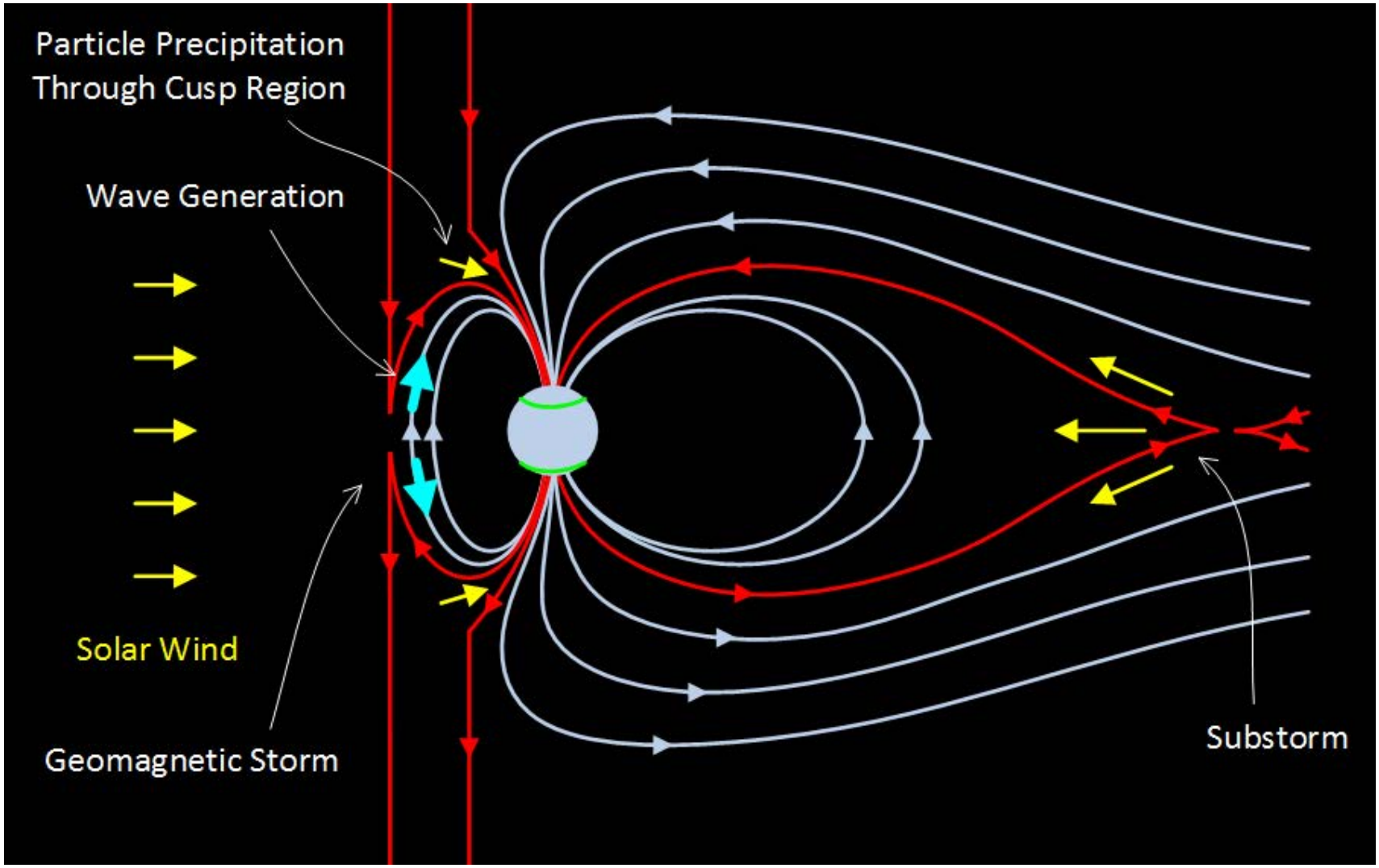


A densely-spaced magnetometer network will help map magnetic field variations and equivalent current systems to study how solar activity affects the geospace system in a finer spatial scale.

Solar-Terrestrial Research



Solar Wind–Magnetosphere-Ionosphere (SW-M-I) Coupling

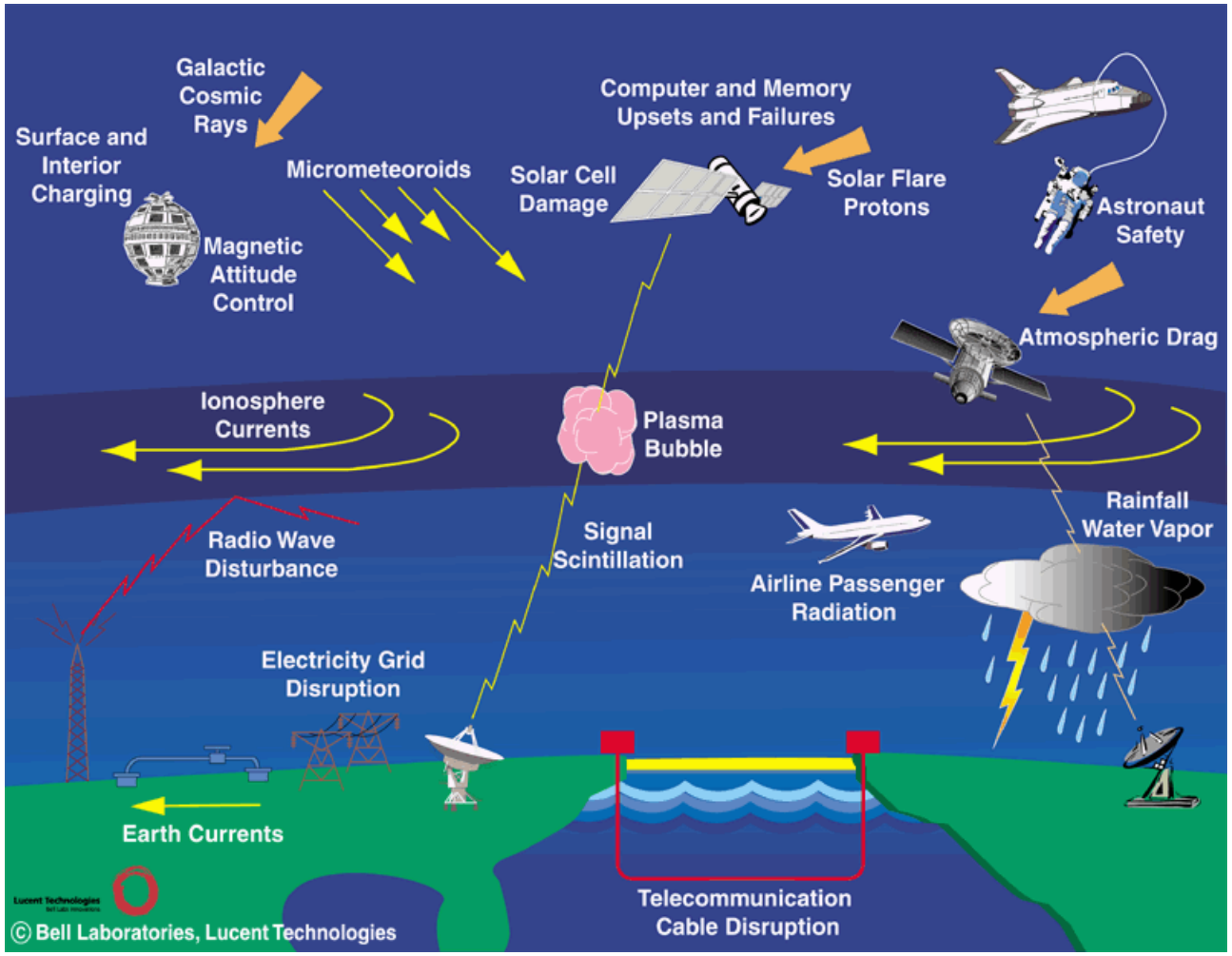


The Arctic and Antarctic regions are where the Earth's magnetic fields are open and connected to the solar wind. Therefore, the energy from the space enters these regions more easily than any other places. ---- So what can we see there?

Why Care?

Space is not benign! (Space Weather)

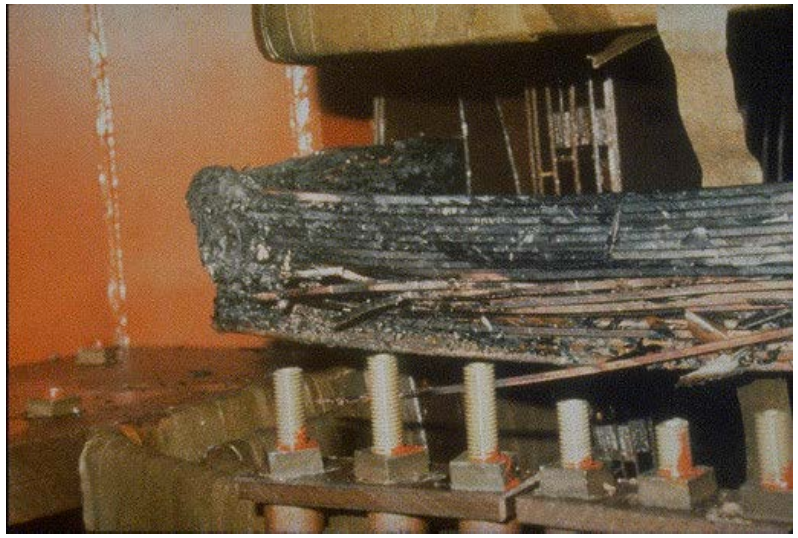
Perturbations to the geospace environment can have huge impacts on society:



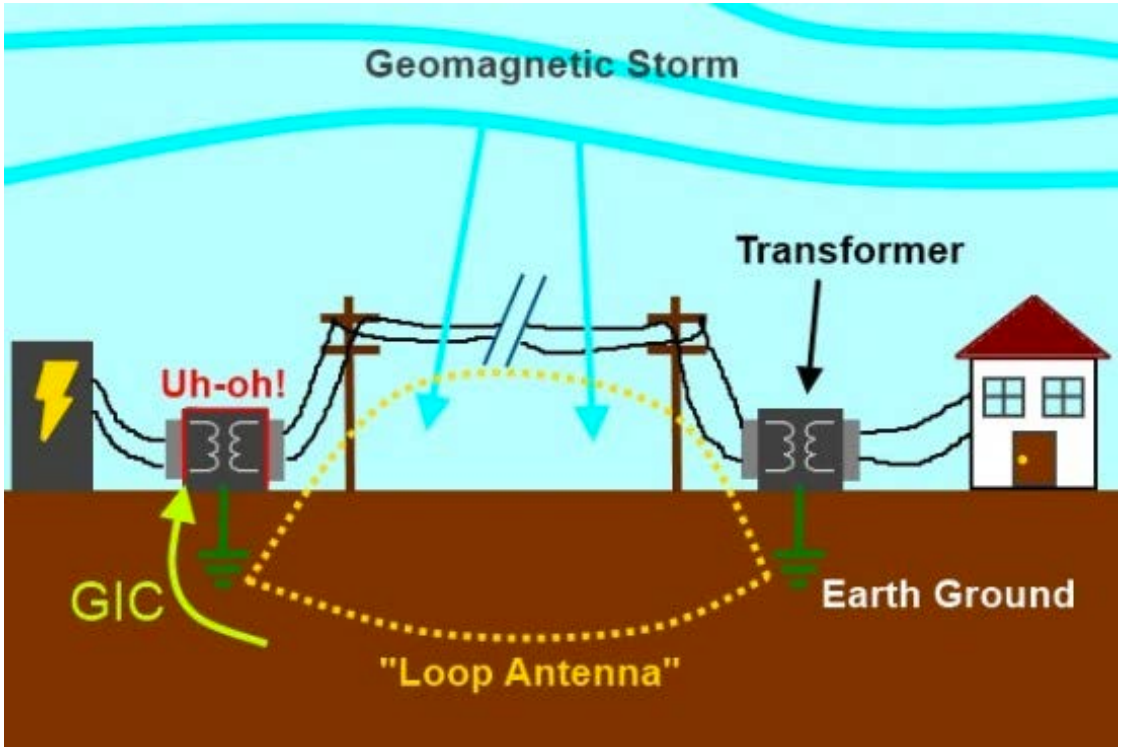
- Spacecraft damage
- Atmospheric drag
- Power disruption
- Human Health (radiation)
- Deviation of airplanes
- Degraded navigation
- Disrupted communication
- Radar clutter
- Confused pigeons!

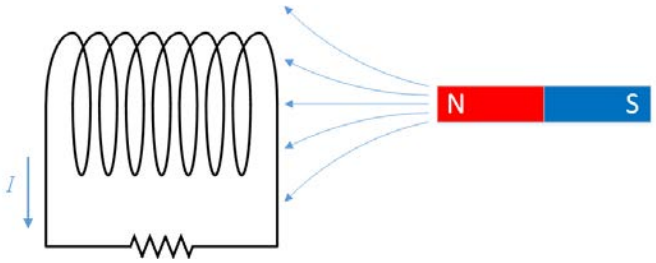
March 13, 1989 Magnetic Storm

- A geomagnetic storm occurred in March 1989 caused the collapse of the entire Hydro-Quebec's electricity transmission system and several at the Salem nuclear plant in NJ, leaving 6 million people without power for more than 9 hours.
- It could takes longer to replace large transformers in case of larger storms.



Ground Effect of Space Weather

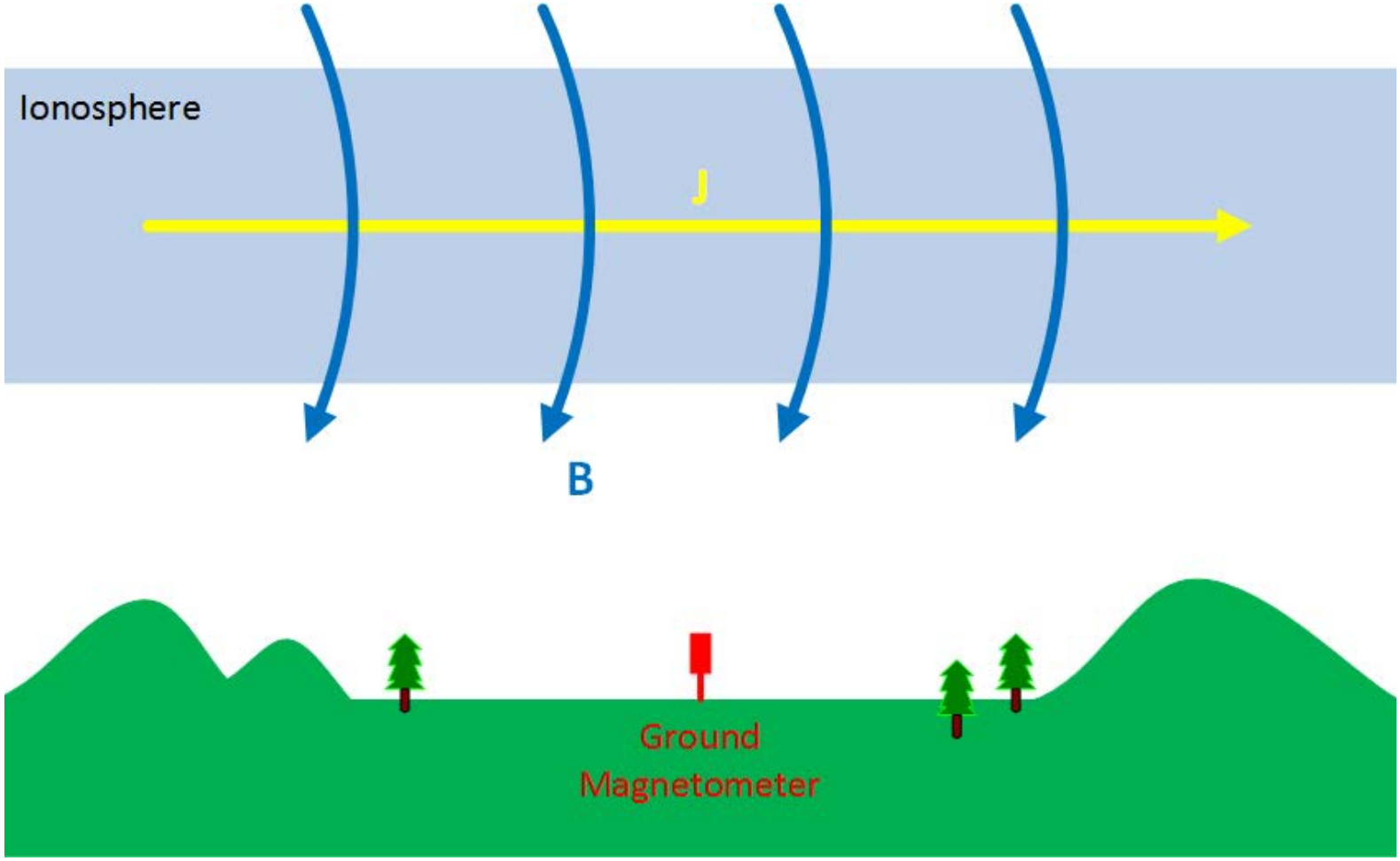




$$\nabla \times \mathrm{E} = -\frac{\partial \mathrm{B}}{\partial t}$$

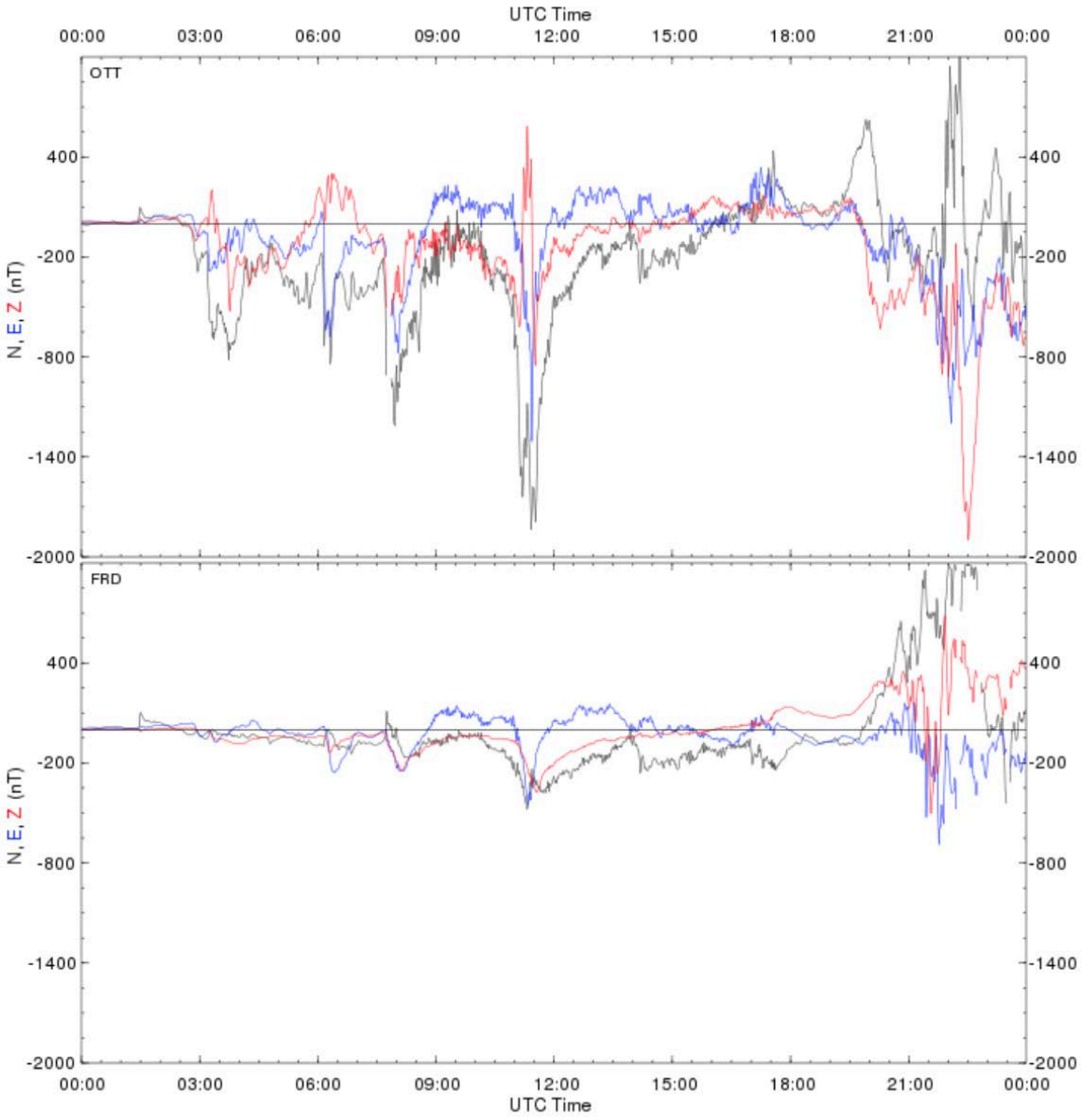
- **Faraday's law of induction**: Changing magnetic fields creates voltage.
- Geomagnetically induced current (GIC)
- Affects transmission lines, oil/gas pipelines railways, etc.

Magnetic Field Measurement on the Ground

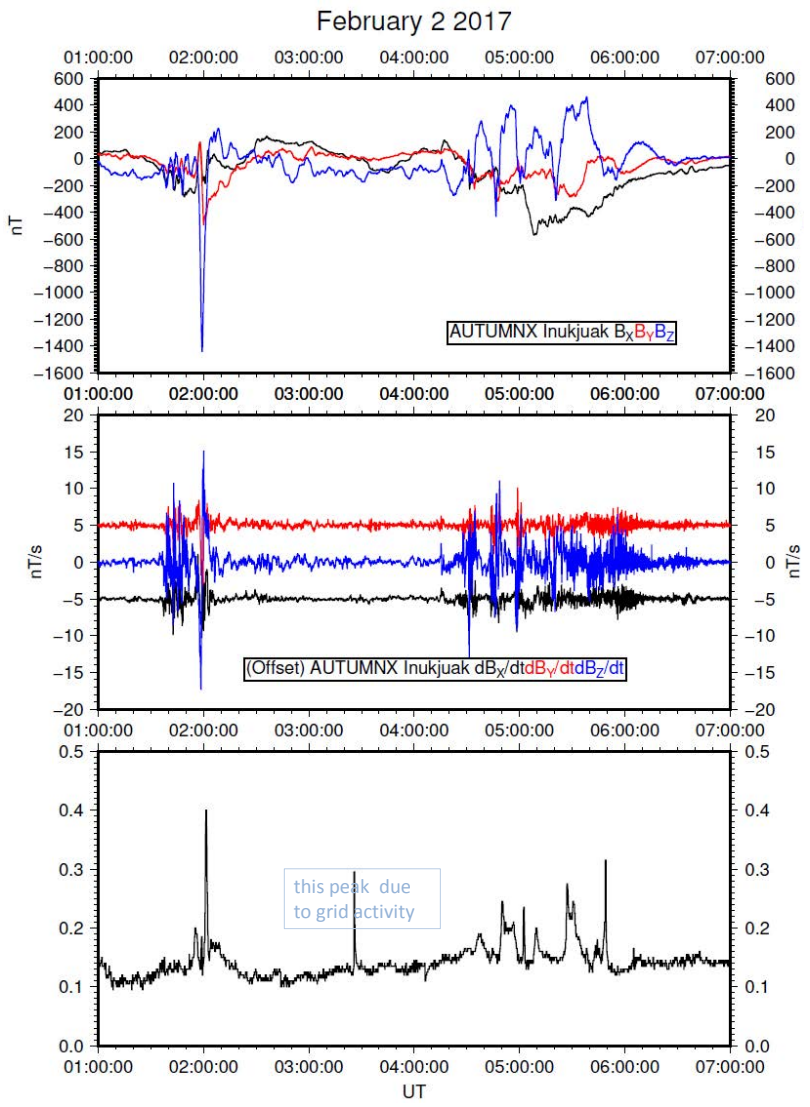


- **Ampere's Circuital Law**: Electric currents produce magnetic fields around the loop that carries the currents.

March 13, 1989 Geomagnetic Storm



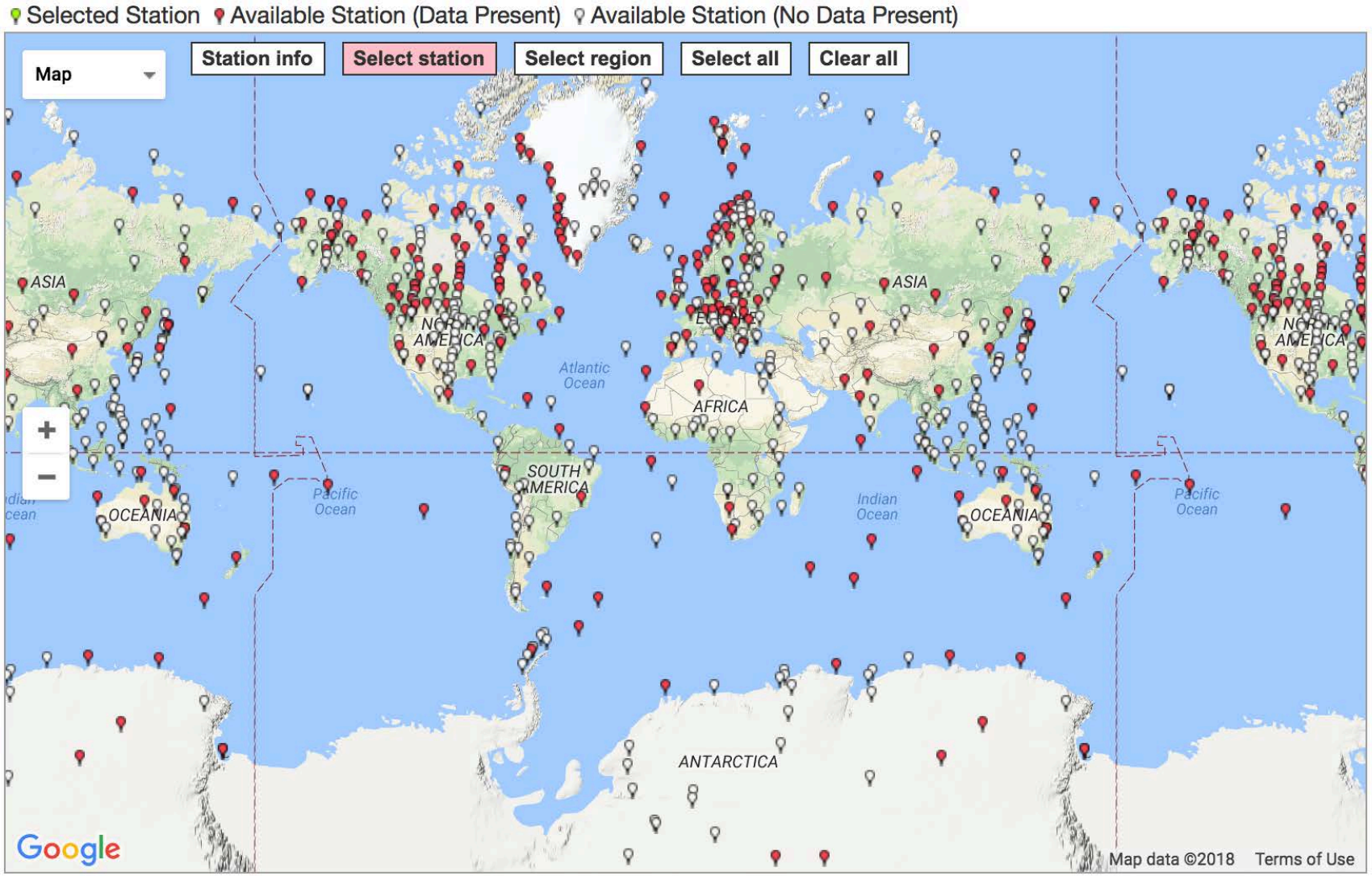
"Magnetic Impulse Event" Observed by Ground Magnetometers



[*Connors et al.* 2017, AGU]

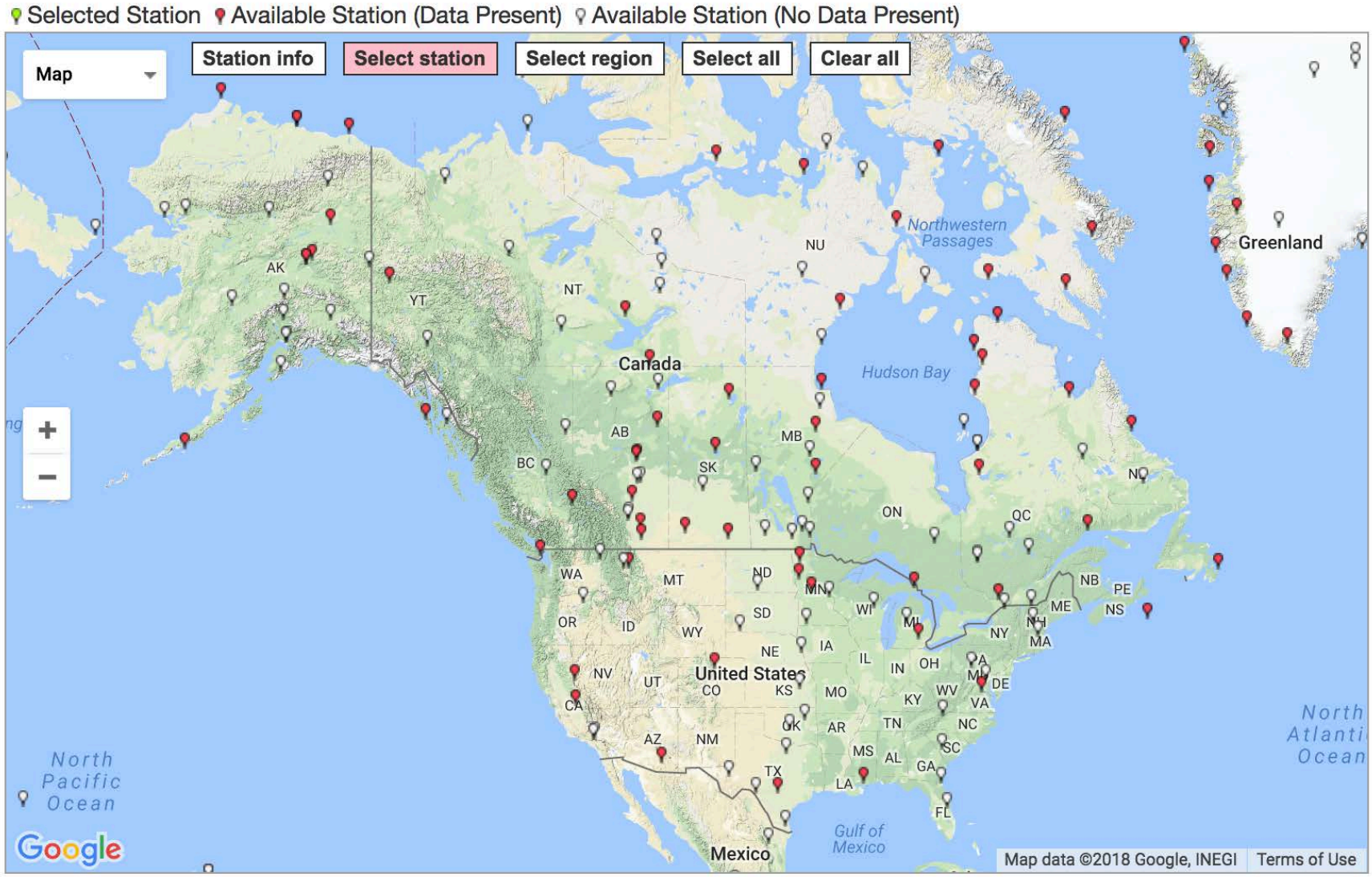
- Inukjuak (INUK) **B** and d**B**/dt correlate with harmonic distortion from Hydro-Québec measurements.
- A few tens of d**B**/dt could cause geomagnetically induced currents (GIC) on the ground.

Example of Magnetometer Network: SuperMAG



Run by JHU/APL, Funded by NSF.

Example of Magnetometer Network: SuperMAG



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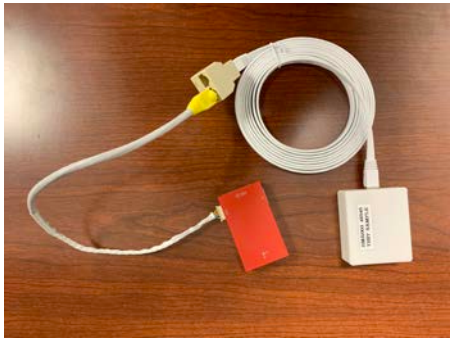
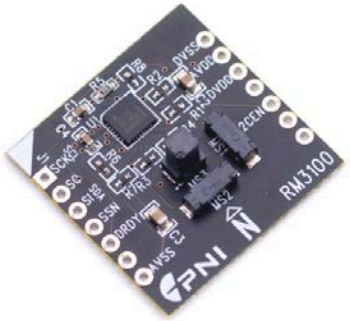
Pro vs HamSCI Magnetometer Array

	"Pro" Magnetometer Array	"HamSCI" Magnetometer Array
Installation	Designated (unmanned, in many cases) observatories (non-magnetic construction) in electromagnetically clean areas.	• Your backyard • Sorry, New Yorkers…
Cost	$$$	Your mortgage or rent? + ~$200-300
Performance Requirement	• Sub nT resolution (< 0.1 nT) vector measurement. • pT-level scalar, absolute measurement (also used for calibration)	~10 nT resolution vector measurement (depending on level of magnetic cleanliness).
Spacing	> Hundreds of miles or depends on science topics.	• Depends on participation • < 50-100 mi expected.
Challenge	• Largely funding-dependent. • Accessibility and maintenance (remote area, internet, local staff) • Vandalism (including wild animals)	Performance may depend on how and where the sensor is installed → needs well-documented protocol.

Proposed Magnetometers for HamSCI SWS

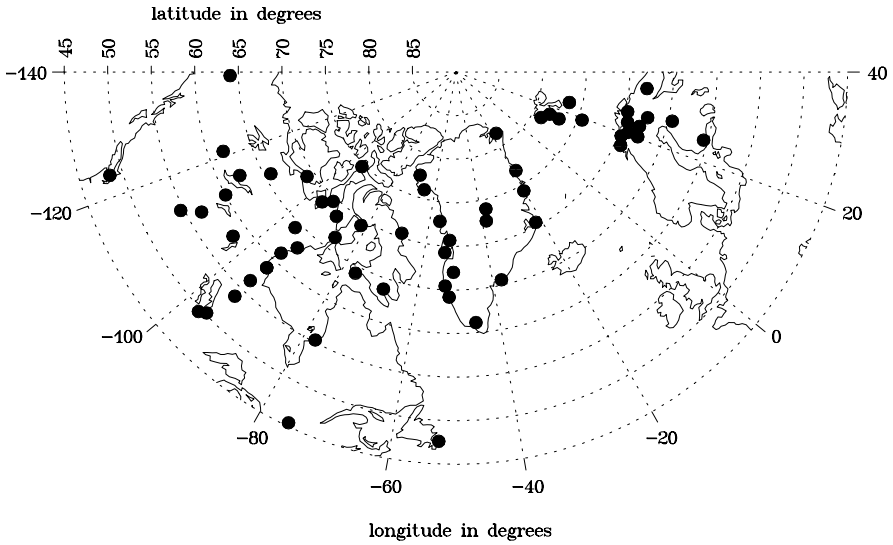
Model	Manufacturer	Features	
Anisotropic Magneto-Resistive (AMR) Magnetometer (Honeywell HMC 1001)	Kyung Hee University/Intorule	• Plug-and-play • ~250 USD (full package including software (Windows)) • ~6 nT resolution	
Magneto-inductive sensor (RM3100)	PNI Sensor	• ~13 nT resolution • 20 USD (sensor only) • Digital output (SPI or I2C)	
Fluxgate FLC3-70	Stefan Mayer Instruments	• ~1 nT resolution • 400 EUR (sensor only) • Analog output	

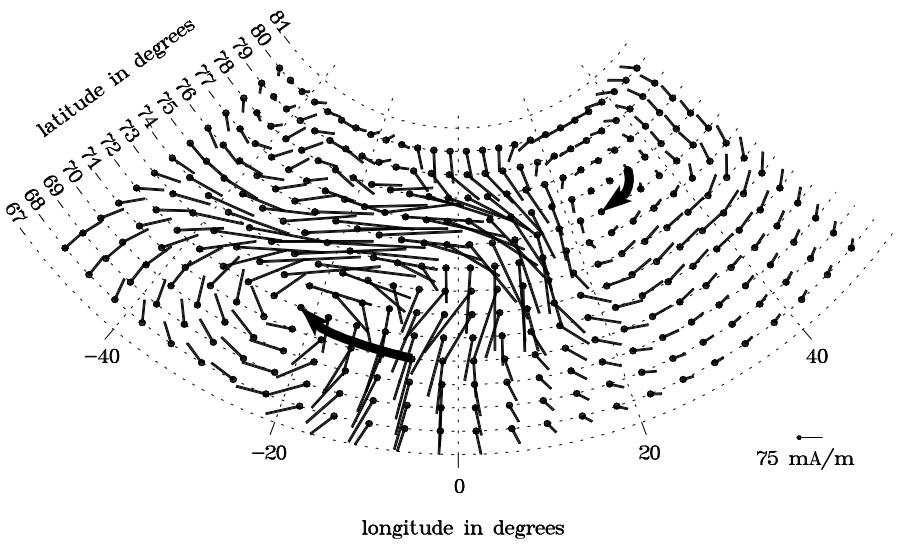
Open Discussion

- Such a citizen-science level, large-scale, densely spaced magnetic field observations have never been done before. There are still many unsolved questions as to how the magnetosphere and ionosphere respond to solar activity in greater details (in terms of spatial scale).
- Space weather research using a densely-spaced magnetometer network
  - What science?
  - Spacing
  - Sensor performance: resolution, sensitivity, noise level, etc.
  - Quality control: installation, EMI issue, etc.

EXTRA SLIDES

"Imaging" Equivalent Current System Using Magnetometer Network

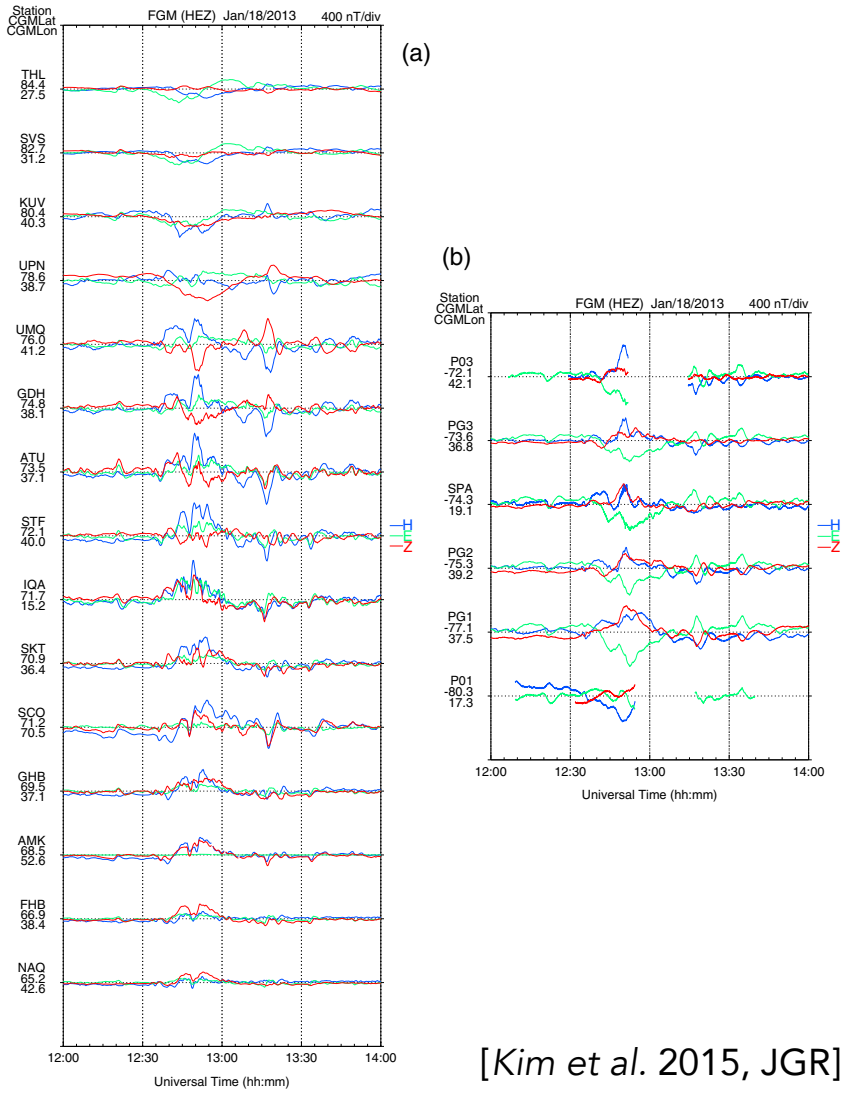




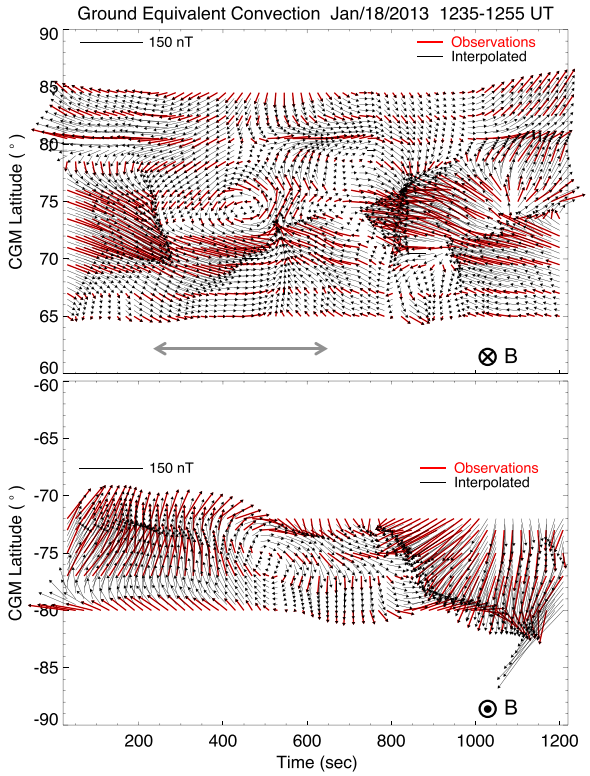
[*Amm et al.* 2002, JGR]

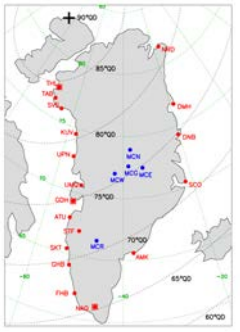
- TCVs over Canada, Europe and Greenland.
- Need more extensive, denser array for finer-scale investigation.

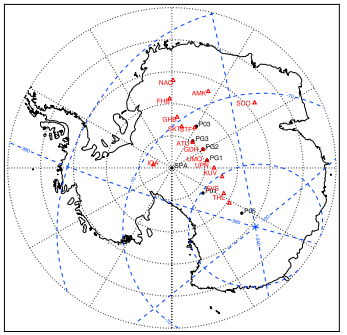
"Imaging" Equivalent Current System Using Magnetometer Network



[*Kim et al.* 2015, JGR]

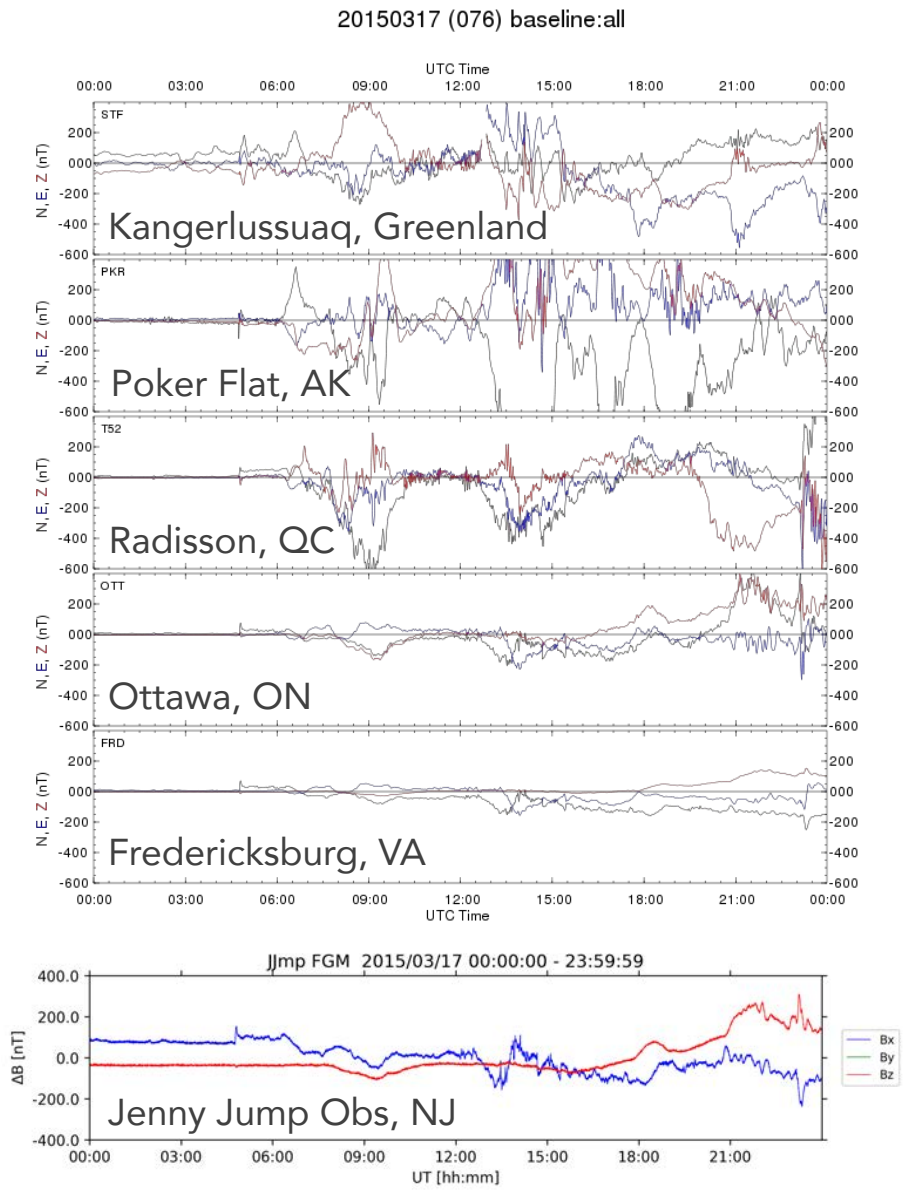




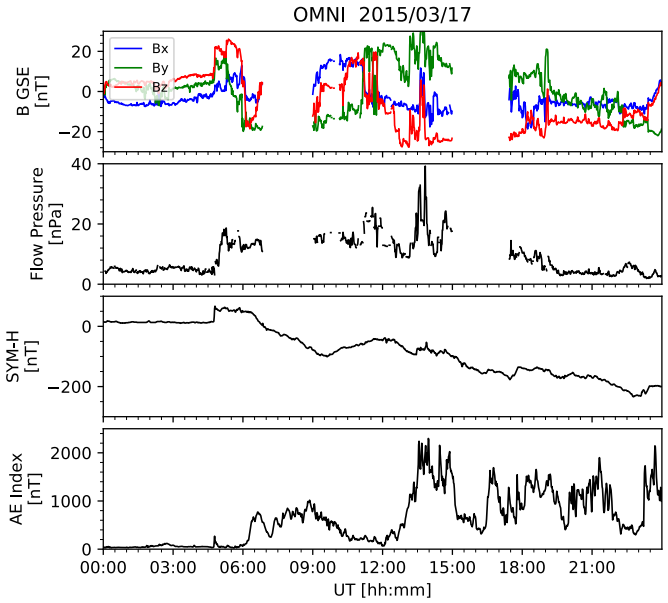


- Ground observations of "Traveling Convection Vortices (TCVs) due to sudden increases in solar wind pressure.
- Shows how the magnetosphere and ionosphere respond to the solar wind flow dynamics.

Geomagnetic Storm Observed by Ground Magnetometers



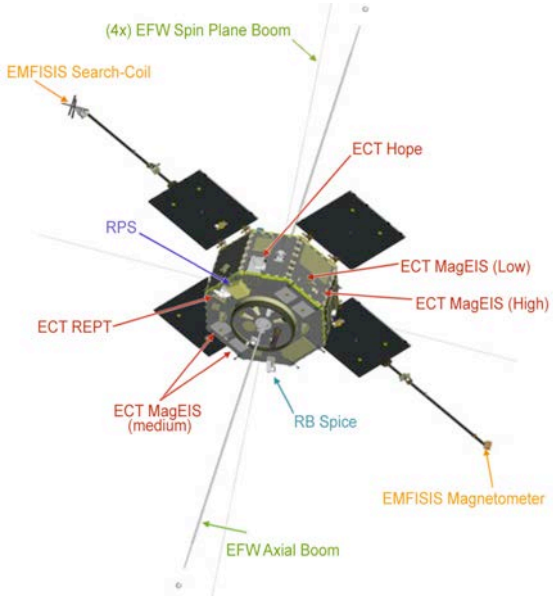
Solar Wind Data

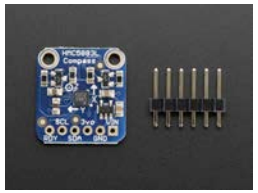


- Several hundreds of nT changes at low/mid latitudes are typical during geomagnetic storms.

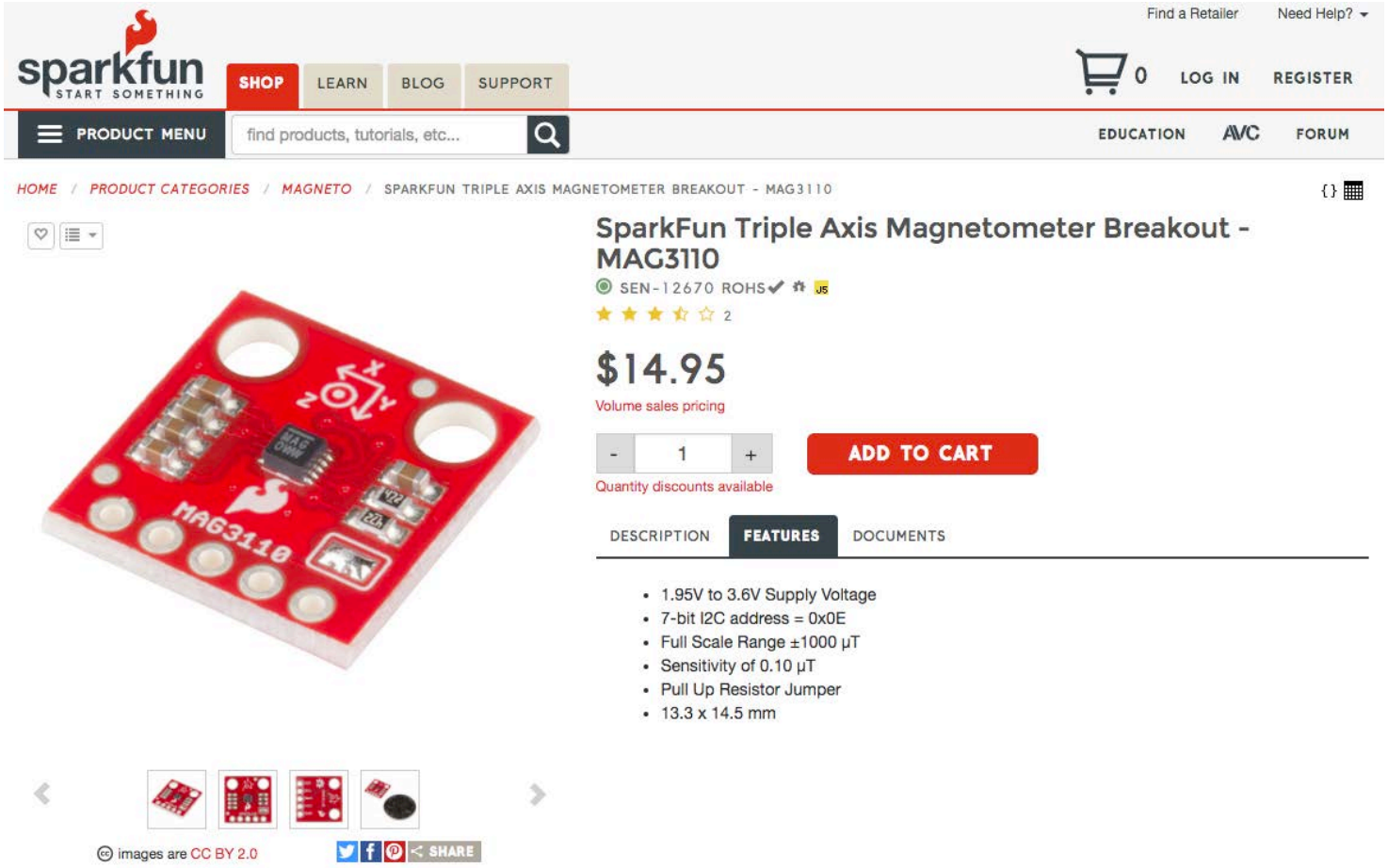
Magnetometers

- Scalar Magnetometers
  - Proton precession
  - Overhauser effect, etc.
- Vector Magnetometers
  - Hall effect
  - Magnetoresistive
  - Fluxgate
  - Search-coil
  - SQUID (Superconducting Quantum Interference Device), etc.





Magneto-Resistive (MR) Magnetometer



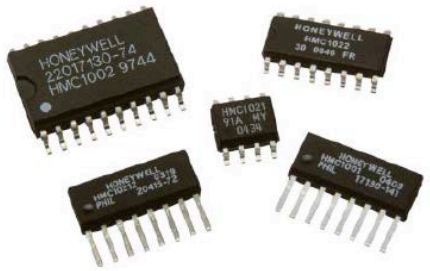
- One of the cheapest kinds but not appropriate for space weather observations: very low resolution (~100 nT).

Anisotropic Magneto-Resistive (AMR) Magnetometer

Honeywell

1- and 2-Axis Magnetic Sensors HMC1001/1002/1021/1022

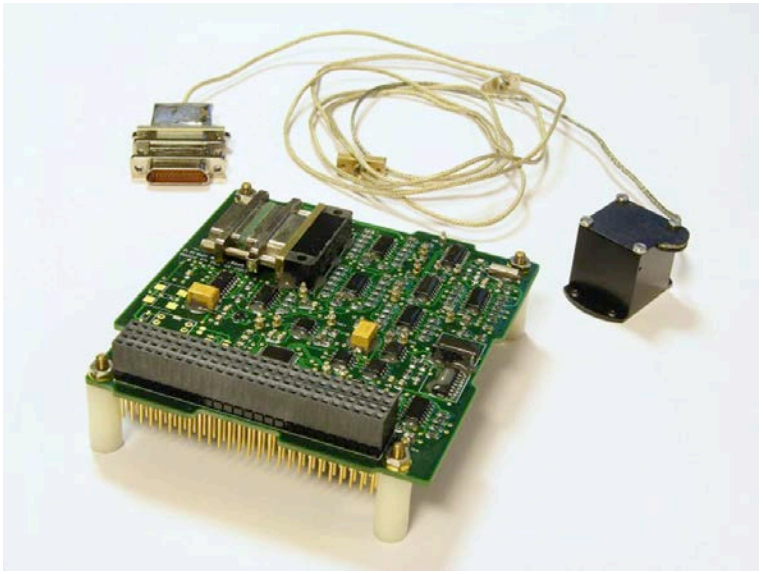
The Honeywell HMC100x and HMC102x magnetic sensors are one and two-axis surface mount sensors designed for low field magnetic sensing. By adding supporting signal processing, cost effective magnetometers or compassing solutions are enabled. These small, low cost solutions are easy to assemble for high volume OEM designs. Applications for the HMC100x and HMC102x sensors include Compassing, Navigation Systems, Magnetometry, and Current Sensing.

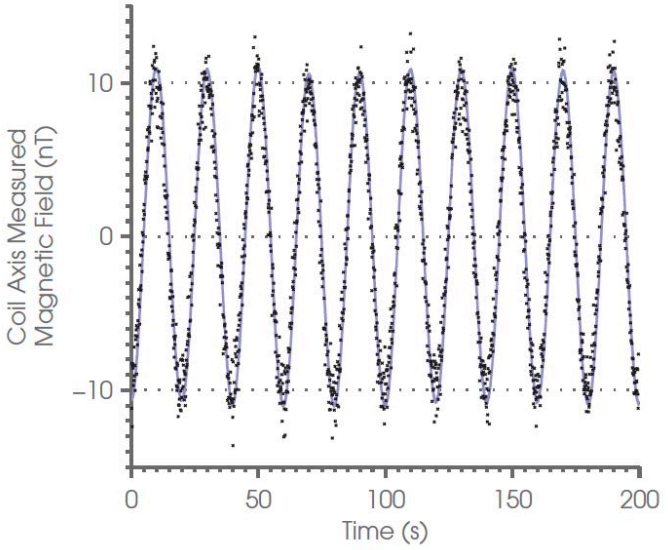


The HMC100x and HMC102x sensors utilize Honeywell's Anisotropic Magnetoresistive (AMR) technology that provides advantages over coil based magnetic sensors. They are extremely sensitive, low field, solid-state magnetic sensors designed to measure direction and magnitude of Earth's magnetic fields, from tens of micro-gauss to 6 gauss. Honeywell's Magnetic Sensors are among the most sensitive and reliable low-field sensors in the industry.

Honeywell continues to maintain product excellence and performance by introducing innovative solid-state magnetic sensor solutions. These are highly reliable, top performance products that are delivered when promised. Honeywell's magnetic sensor solutions provide real solutions you can count on.

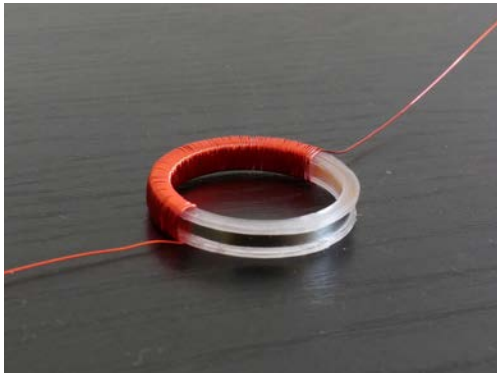
FEATURES	BENEFITS
Surface Mount 1 and 2-Axis Sensors	Easy to Assemble & Compatible with High Speed SMT Assembly
Low Cost	Designed for High Volume, Cost Effective OEM Designs
4-Element Wheatstone Bridges	Low Noise Passive Element Design
Low Voltage Operations (2.0V)	Compatible for Battery Powered Applications
Available in Tape & Reel Packaging	High Volume OEM Assembly
Patented Offset and Set/Reset Straps	Stray Magnetic Field Compensation
Wide Field Range (up to +/-6 Oe)	Sensor Can Be Used in Strong Magnetic Field Environments

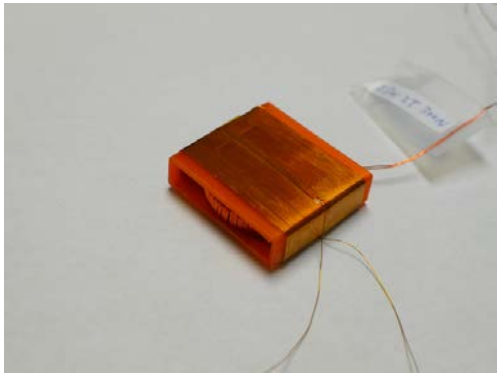


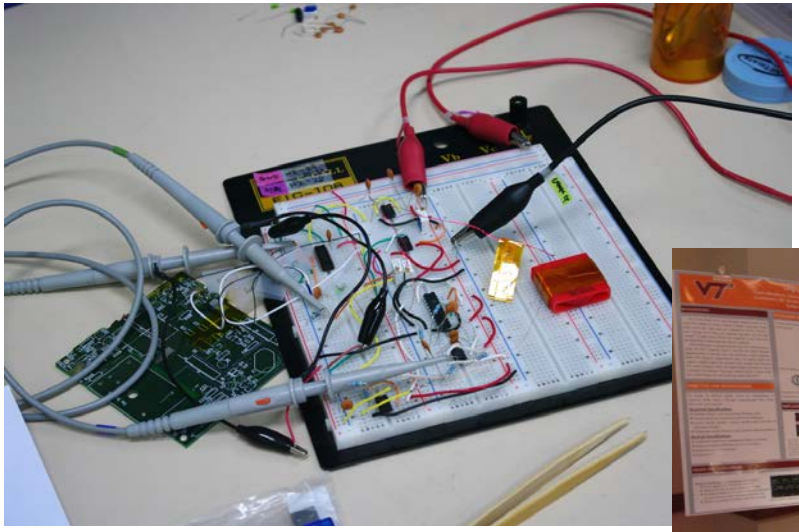


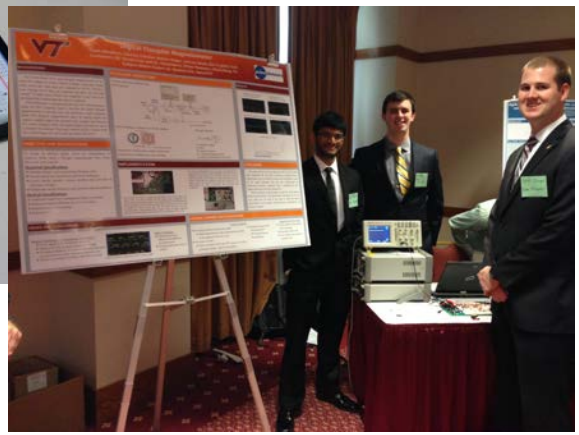
- Adequate resolution for scientific use: ~3 nT [Brown et al., Rev. Sci. Inst. 2014].

In-House Fluxgate Magnetometer









- Prototype fluxgate magnetometer as part of Virginia Tech ECE independent study project.
- Sensor: magnet wire, amorphous metal alloy ribbon, 3-D printed bobbins. Coils are wound by hand → Great Hands-on experience!
- Electronics: can be either analog or digital. Most components are inexpensive.

In-House Fluxgate Magnetometer

- Challenges
  - Material/parts could be very low; however, labor-intensive (machining, coil-winding, electronics fabrication, test/calibration).
  - Quality control: calibration, installation, EMI issues, etc.