The CARISMA Magnetometer Array

David Milling
Andy Kale
University of Alberta

UNIVERSITY OF ALBERTA

Space Environment Canada (SEC)

Institute	PI	Network	Instruments
U Calgary (PI)	Eric Donovan	TREx	All sky imagers Riometer, Meridan Imaging Spectrographs
U Alberta	Ian Mann	CARISMA	Fluxgate Magnetometers Induction Coil Magnetometers
U Athabasca	Martin Connors	AUTUMN	Fluxgate Magnetometers

CARISMA has operated with CSA funding as part of SEC since April 2023.

UNIVERSITY OF ALBERTA

Student Survey

1. How many of you have used Magnetic Field data in your research?

2. How many of you work in designing or building instrumentation?

3. How many of you work with instrumentation (of any kind) in the field?

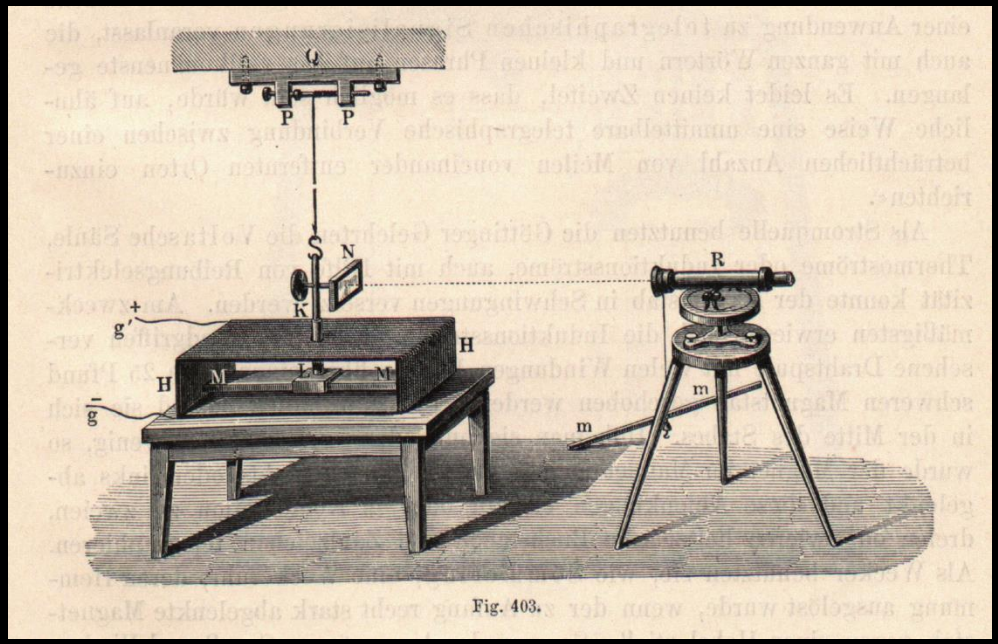
UNIVERSITY OF ALBERTA

Focus

- Introduction to ground based magnetic field sensors
- CARISMA
- Operational Challenges
- Data and data products

UNIVERSITY OF ALBERTA

Early Magnetic Field Sensors

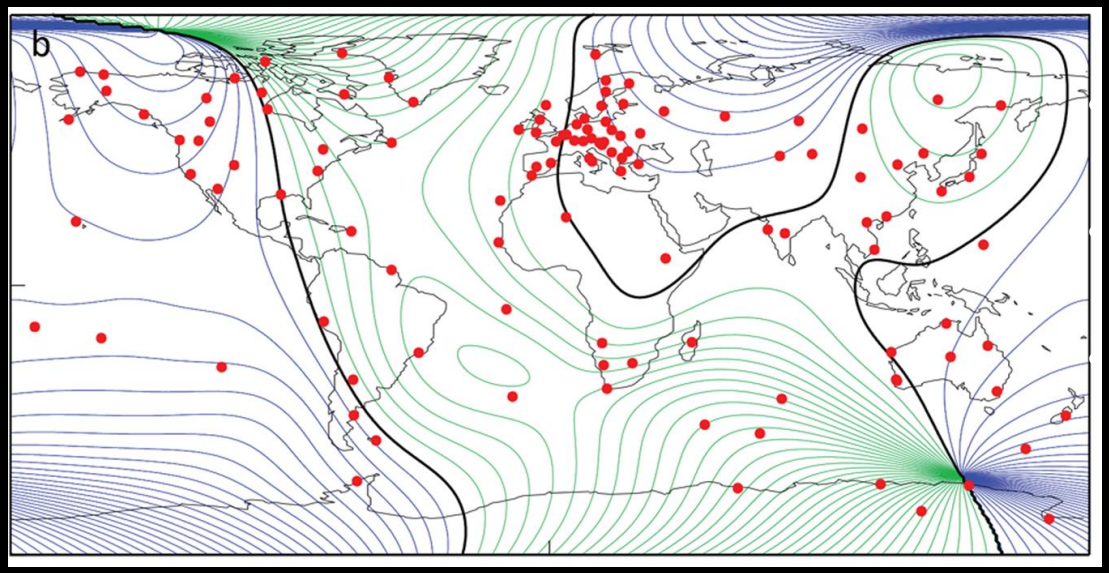


Gauss-Weber Magnetometer ca. 1833

First absolute values of the Earth's magnetic field

UNIVERSITY OF ALBERTA

Global Magnetic Observatories



Accurate Absolute Measurements of Earth's B

INTERMAGNET; ~ 150 observatories

Long term monitoring – some as old as 150 years.

- Magnetic reference field models:
  - International Geomagnetic reference Field (IGRF)
  - World Magnetic Model (WMM)

- Magnetic indices:
  - Planetary K-index - Kp
  - Disturbance Storm Time Index - Dst
  - Auroral Electrojet Index - AE

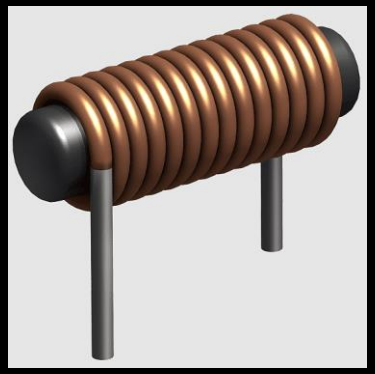
Types of magnetometer

Scalar |B|	Applications
Proton precession	Observatories
Overhauser	Observatories Geophysics
Alkali Vapour	Geophysics
Helium-4	Biomedical Space (SWARM)

Vector Bx, By, Bz	Applications
Hall effect	Automotive
Magnetoresistive	Electronic compasses
SQUID	Laboratory Medical
Induction Coil	Geophysics Space Physics
Fluxgate	Submarine detection Observatories Geophysics Space Physics

Faraday's Law of Induction

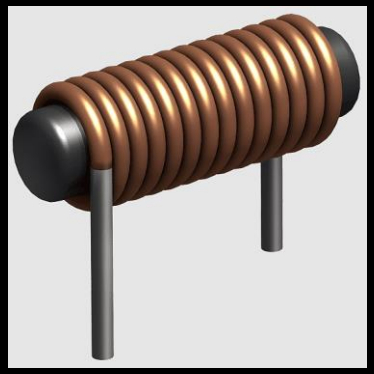
Faraday's Law for a coil of wire with a permeable core



$$\varphi = NA\,\mu_0\mu_r H \qquad V = \frac{d\varphi}{dt}$$

Faraday's Law of Induction

Faraday's Law for a coil of wire with a permeable core

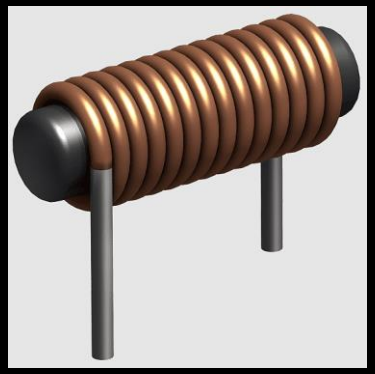


$$\varphi = NA\,\mu_0\mu_r H \qquad V = \frac{d\varphi}{dt}$$

$$V = (NA\mu_0\mu_r)\frac{dH}{dt} + (N\mu_0\mu_r H)\frac{dA}{dt} + (NA\mu_0 H)\ \frac{d\mu_r}{dt}$$

Faraday's Law of Induction

Faraday's Law for a coil of wire with a permeable core



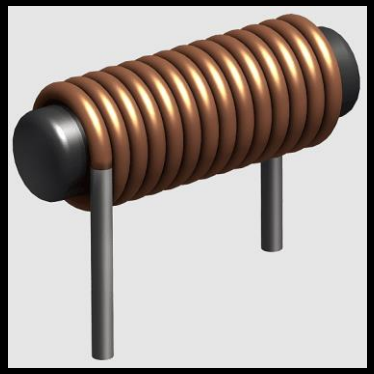
$$\varphi = NA\,\mu_0\mu_r H \qquad V = \frac{d\varphi}{dt}$$

$$V = \boxed{(NA\mu_0\mu_r)\frac{dH}{dt}} + (N\mu_0\mu_r H)\frac{dA}{dt} + (NA\mu_0 H)\frac{d\mu_r}{dt}$$

Induction Coil

Faraday's Law of Induction

Faraday's Law for a coil of wire with a permeable core



$$\varphi = NA\,\mu_0\mu_r H \qquad V = \frac{d\varphi}{dt}$$

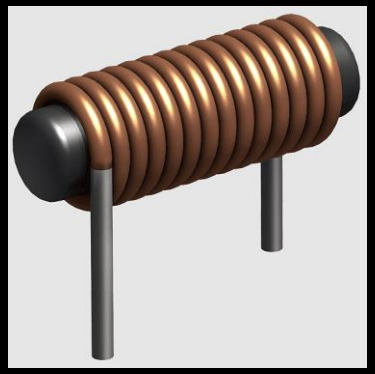
$$V = \boxed{(NA\mu_0\mu_r)\frac{dH}{dt}} + \boxed{(N\mu_0\mu_r H)\frac{dA}{dt}} + (NA\mu_0 H)\ \frac{d\mu_r}{dt}$$

Induction Coil

Rotating coil

Faraday's Law of Induction

Faraday's Law for a coil of wire with a permeable core



$$\varphi = NA\,\mu_0\mu_r H \qquad V = \frac{d\varphi}{dt}$$

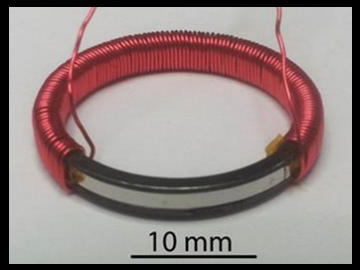
$$V = (NA\mu_0\mu_r)\frac{dH}{dt} + (N\mu_0\mu_r H)\frac{dA}{dt} + (NA\mu_0 H)\frac{d\mu_r}{dt}$$

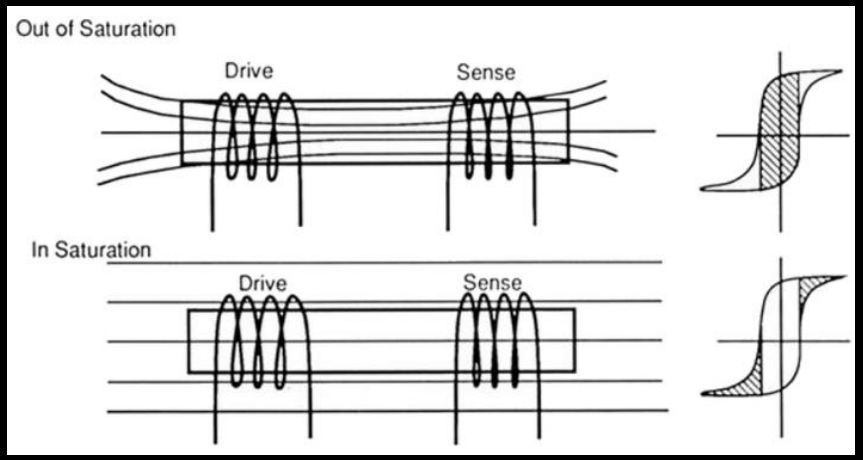
Induction Coil

Rotating coil

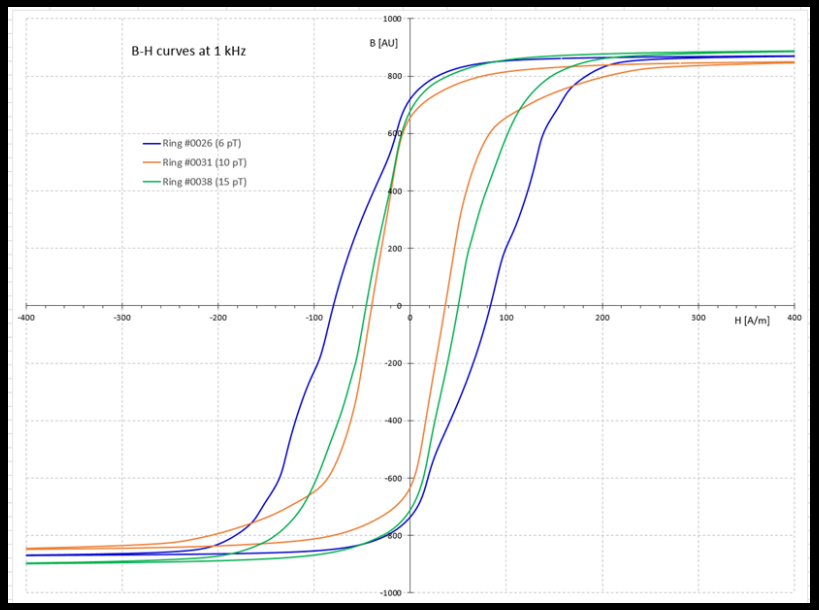
Fluxgate

The “Flux Gate”





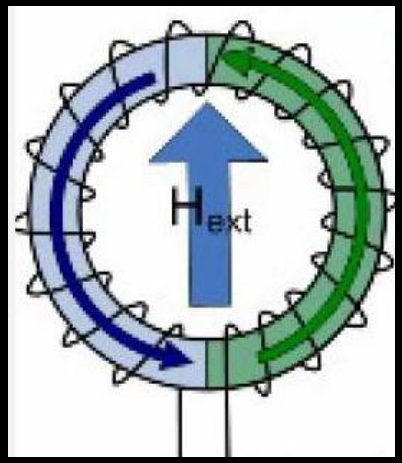
Credit: Lenz and Edelstein, 2006

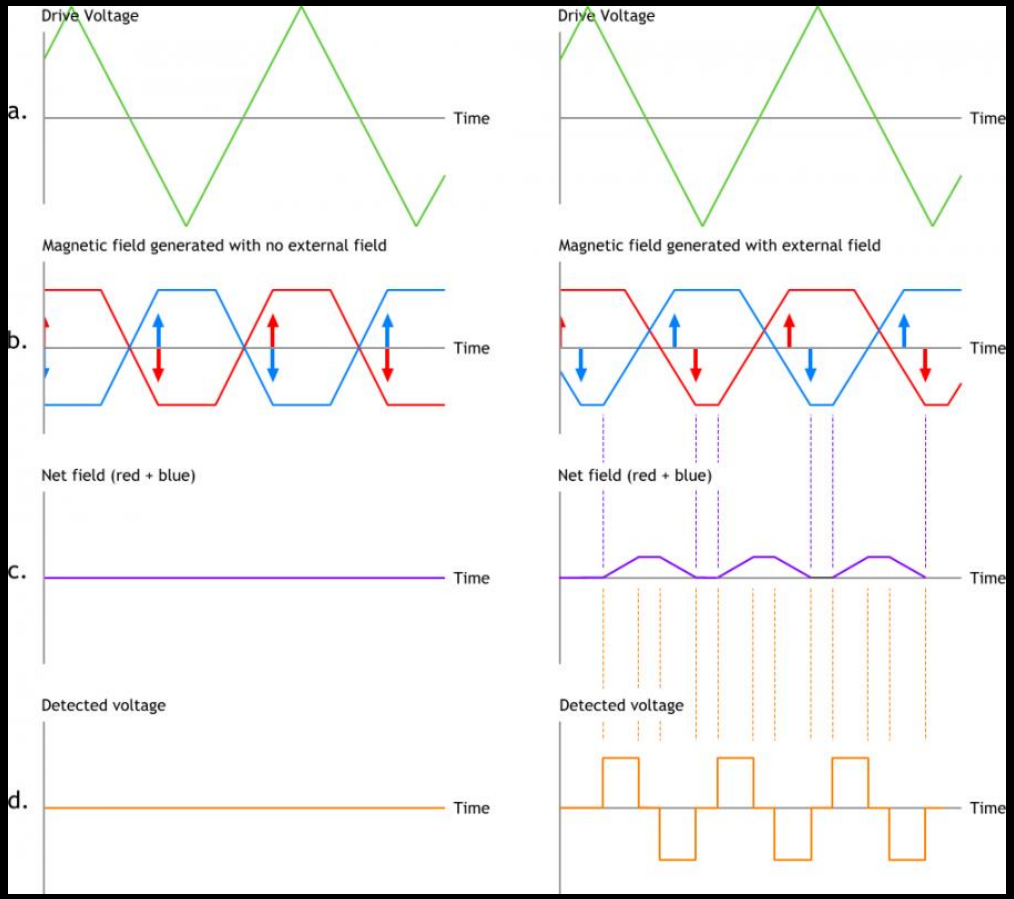


B-H curves of fluxgate core material driven into saturation at 1 kHz

UNIVERSITY OF ALBERTA

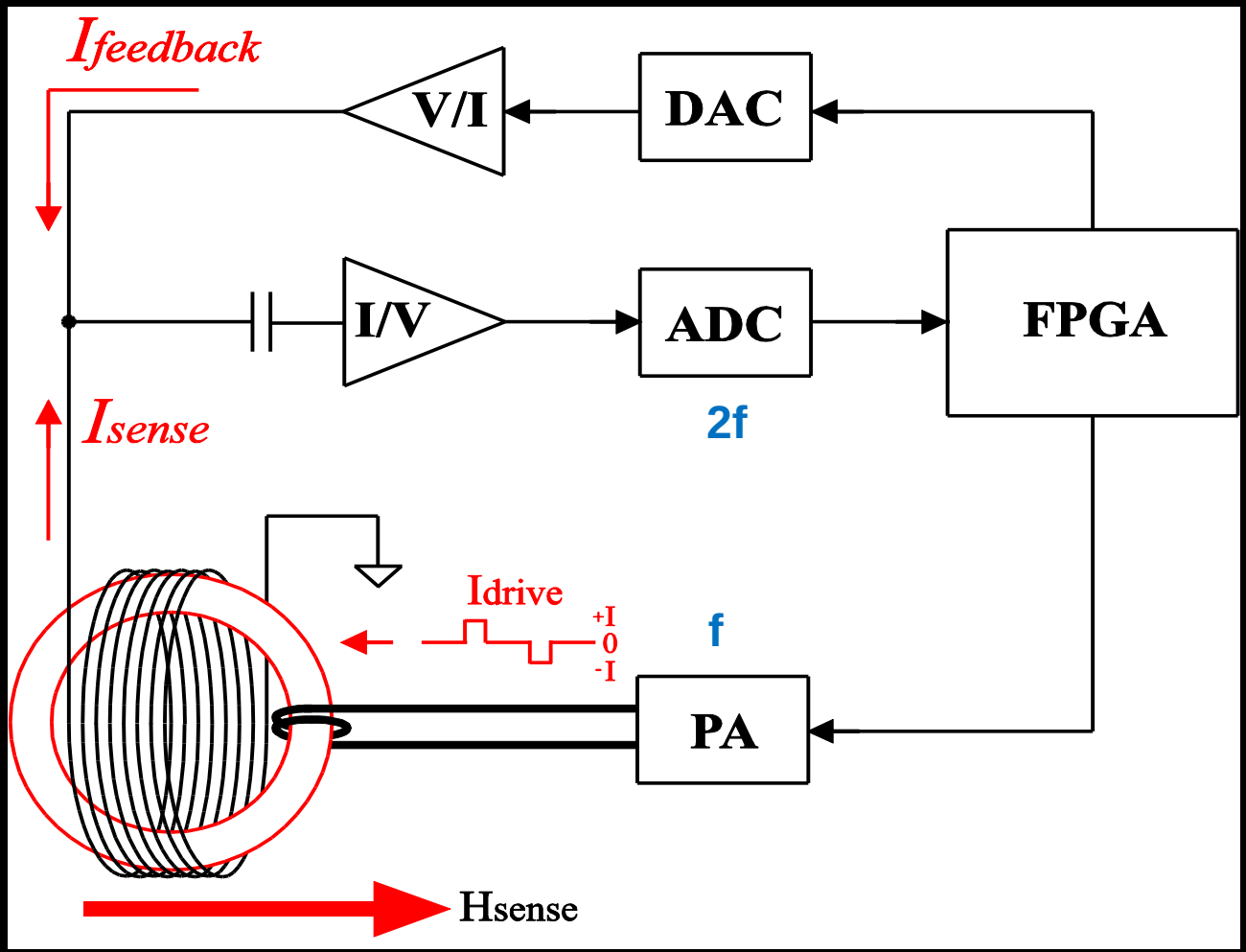
The “Flux Gate”





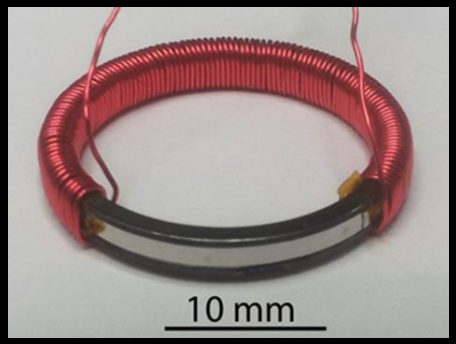
UNIVERSITY OF ALBERTA

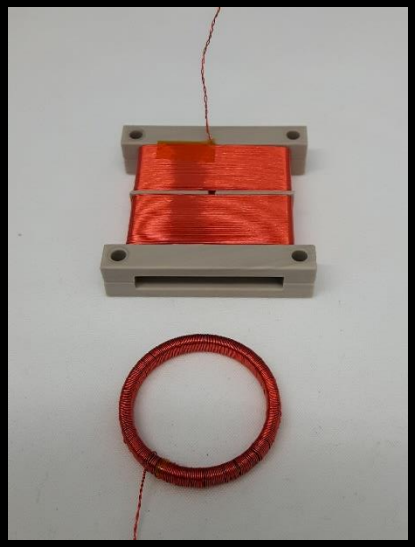
Digital Fluxgate Magnetometer

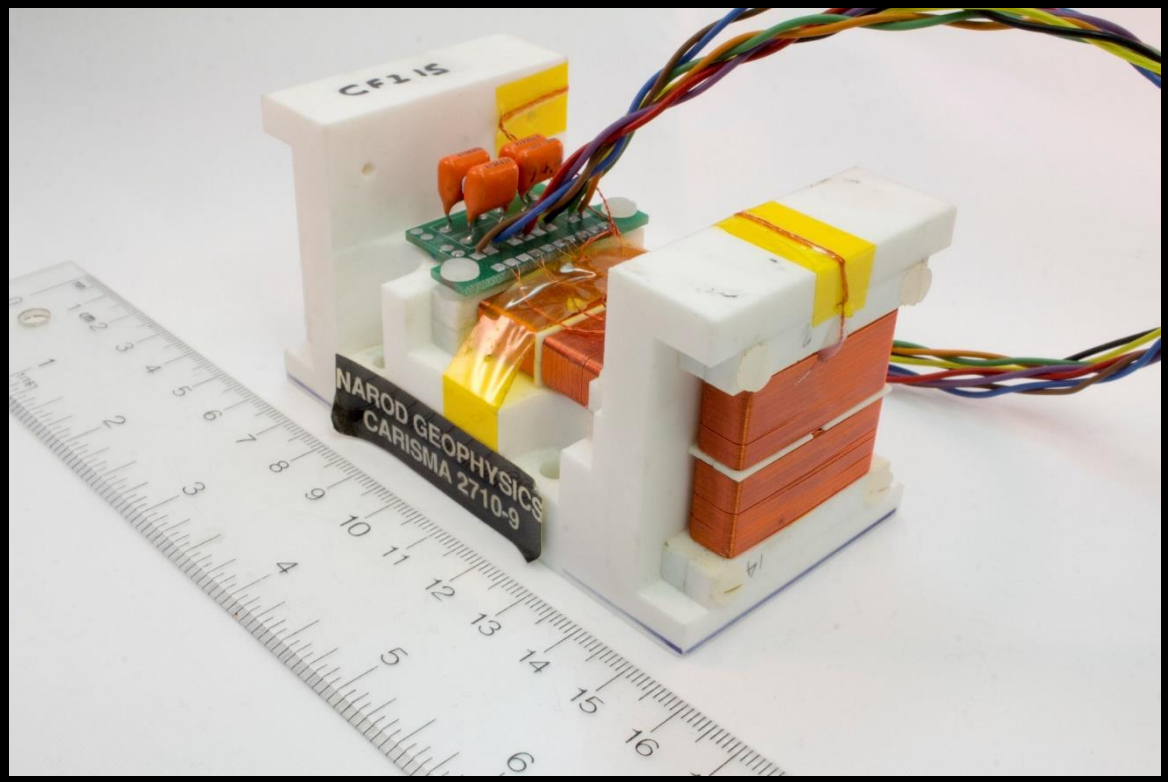


From: Miles et al, 2016

3-axis Fluxgate Sensor







UNIVERSITY OF ALBERTA

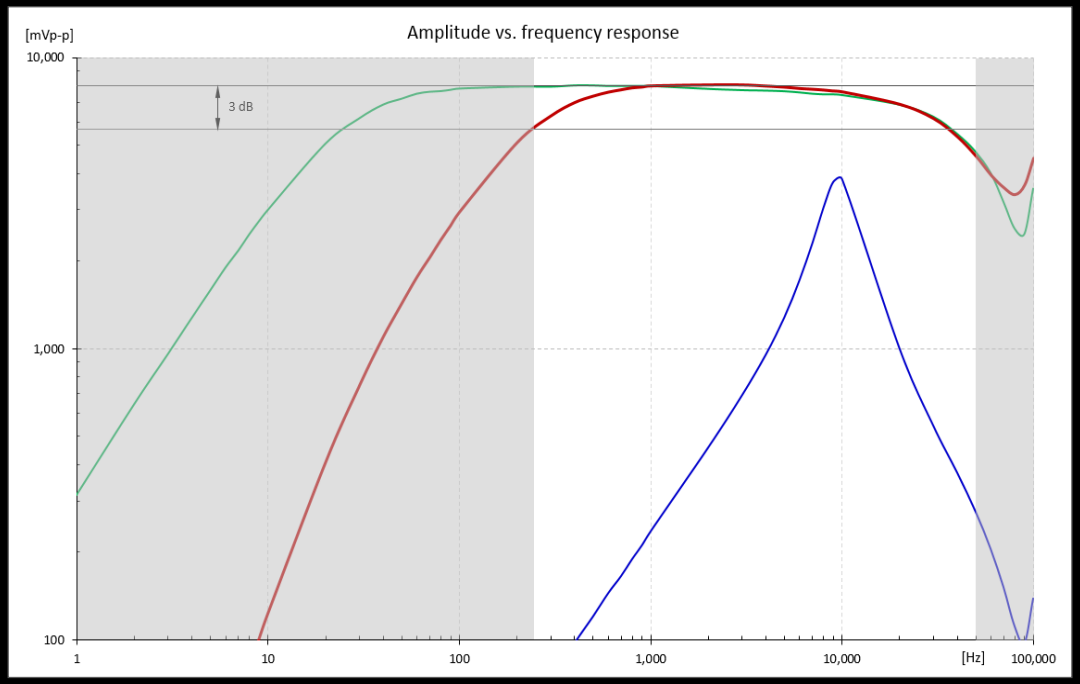
CARISMA Fluxgate Magnetometer

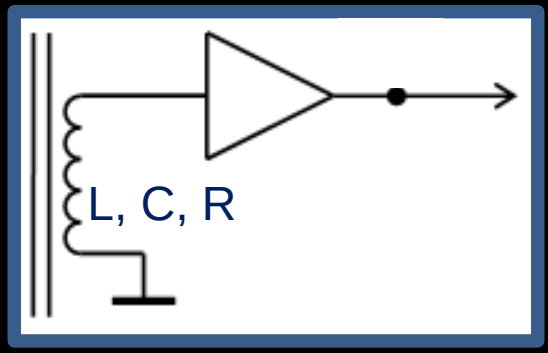
- Narod Geophysics Ltd - Observatory grade magnetometer
- Near-Continuous measurements for over 35 years at core sites

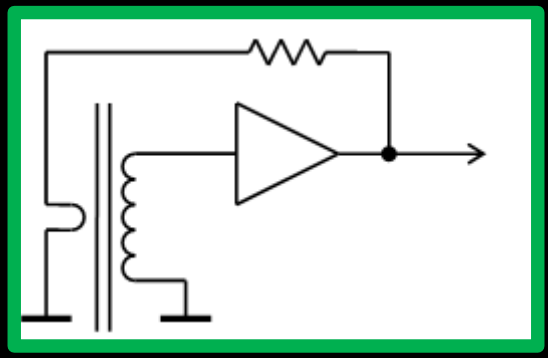
Dynamic Range (nT)	± 70,000
Frequency Range	DC – 2 Hz
Resolution (nT)	0.025
Temp stability (nT/°C)	< 0.1
Drift (nT/day)	< 0.01
Noise (pT/√Hz @ 1Hz)	7 - 20
Sampling rate (sps)	8
Power (W avg)	< 1.3
Interface	RS-232

UNIVERSITY OF ALBERTA

Induction Coil Magnetometer: Frequency Response

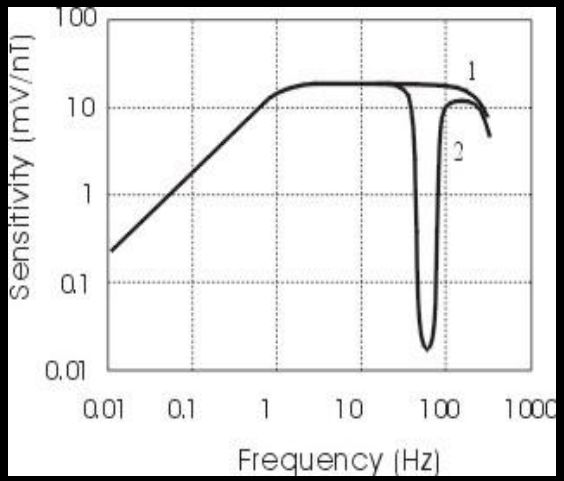






UNIVERSITY OF ALBERTA

CARISMA Induction Coil Magnetometer



Bandwidth			0.01–30 Hz
Transfer Function	0.01–1 Hz		Linear
	1–30 Hz		Flat
Sensitivity	Channel 1	Linear	20×f mV/nT
		Flat	20 mV/nT
	Channel 2	Linear	200×f mV/nT
		Flat	200 mV/nT
Sensitivity Error			< 1 dB
Magnetic Noise Level			< 0.2 pT/√Hz at 1 Hz
Noise Rejection			>> 60 dB at 60 Hz
Power Supply			±12 V
Temperature Range			-30°C to +50°C

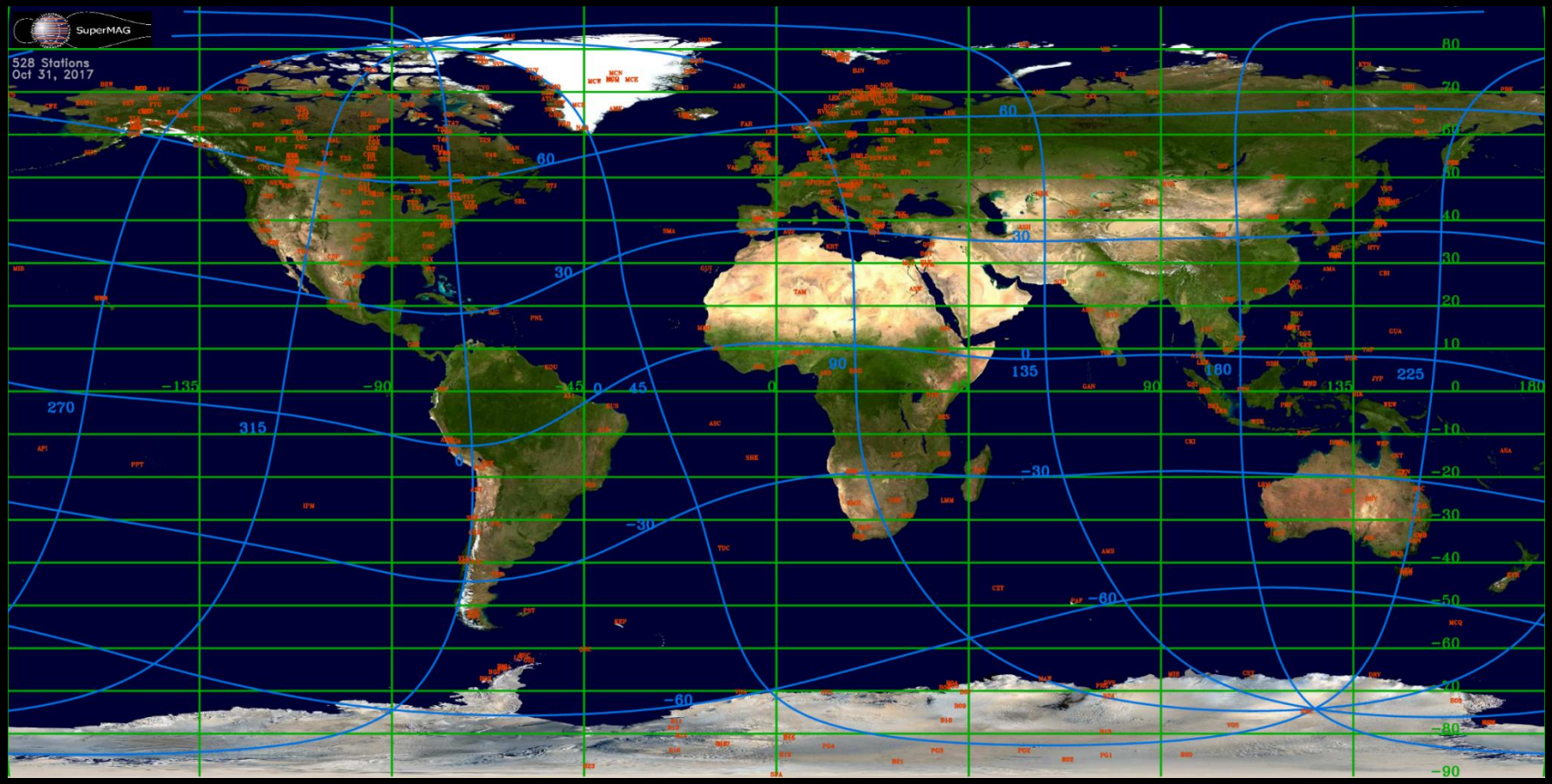
UNIVERSITY OF ALBERTA

Scientific Magnetometer Arrays

- Location driven by science needs - regions which aren't covered by observatories
- Provide support for specific space missions e.g. THEMIS
- Higher spatial resolution
- Maybe higher time resolution

- Reliant on research funding – may not be long term
- No baseline control – operate as "variometers" (no problem for most space physics research)

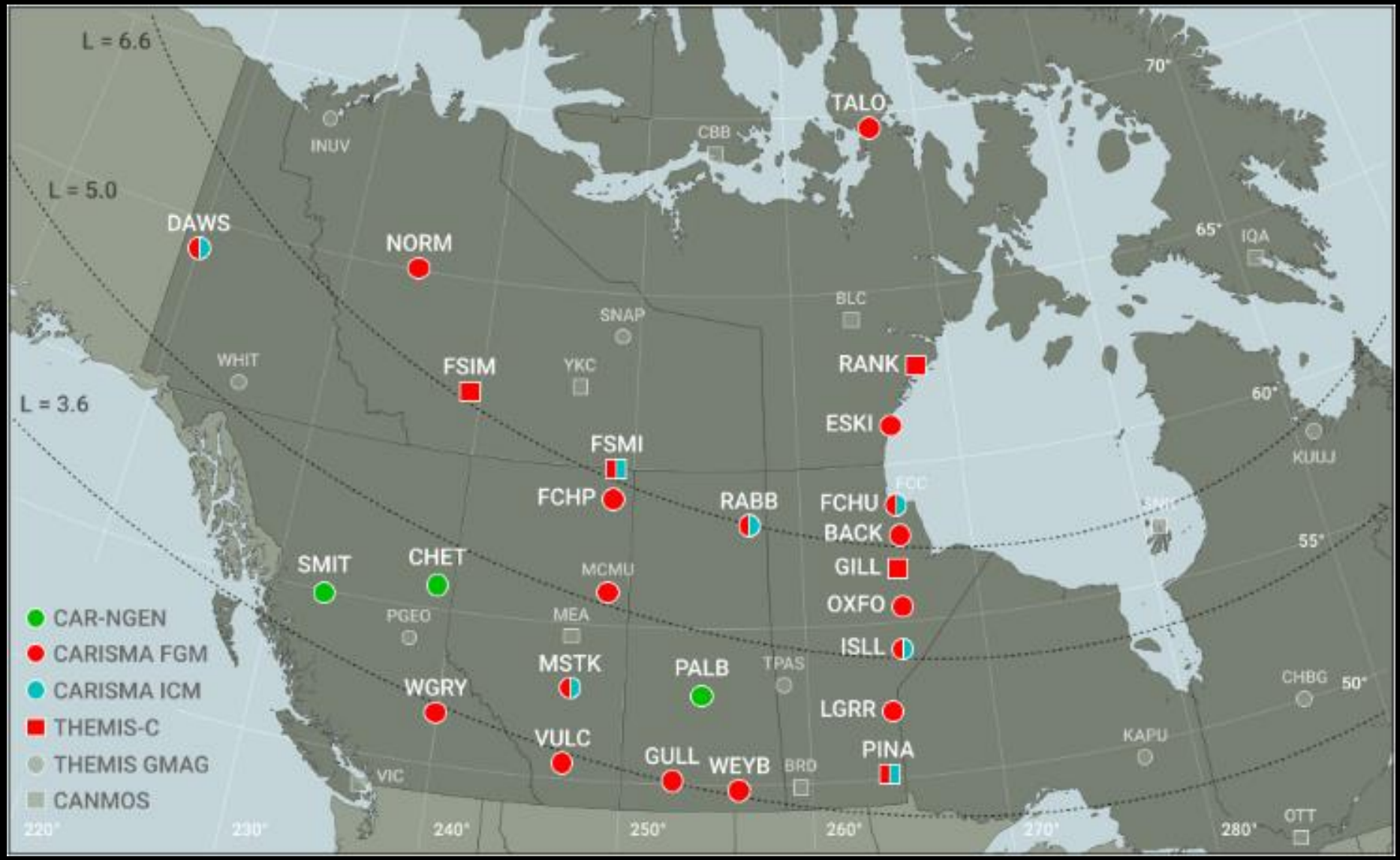
SuperMAG.jhuapl.edu



528 Stations Contributing to SuperMAG (2017)

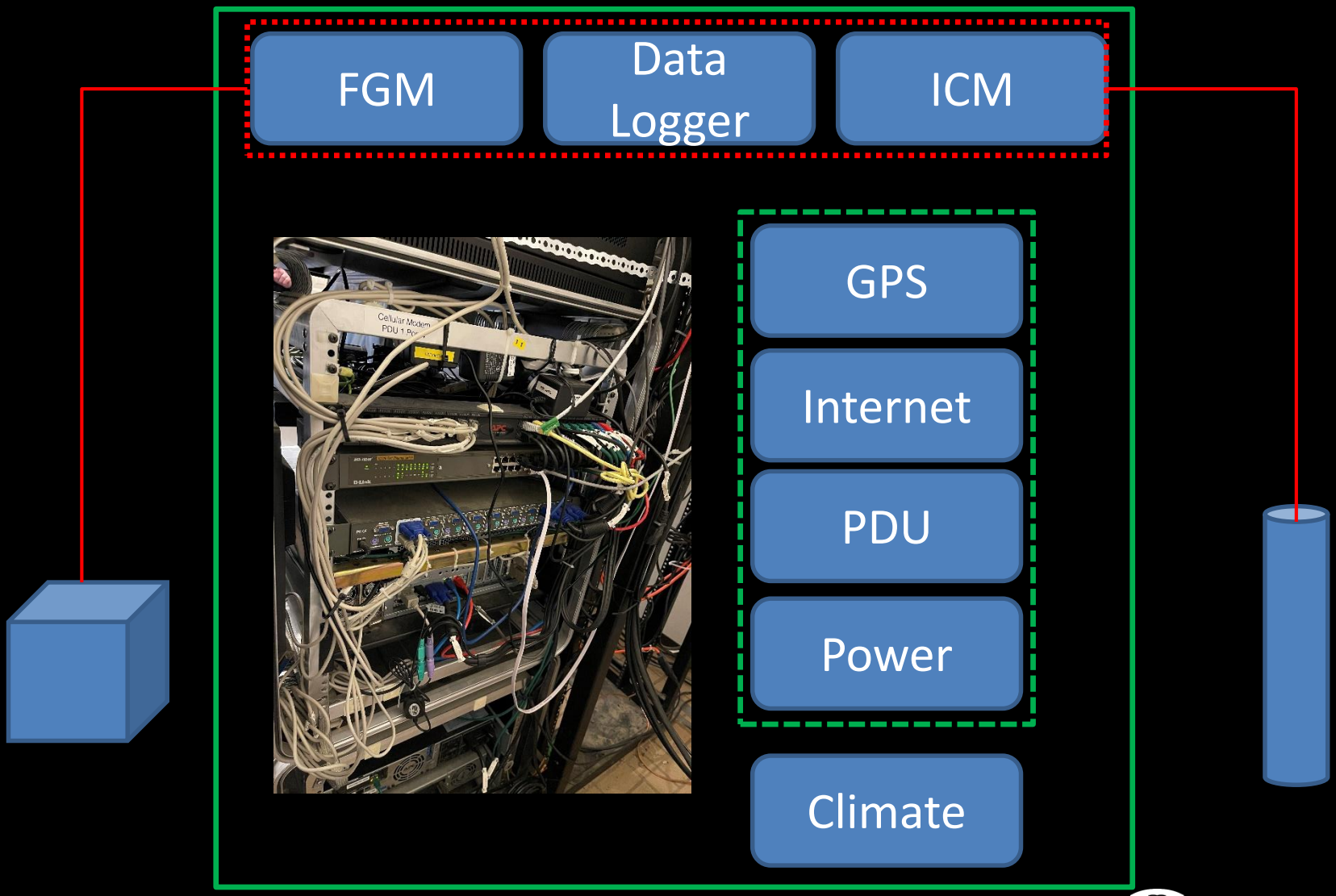
UNIVERSITY OF ALBERTA

CARISMA Magnetometers



UNIVERSITY OF ALBERTA

Anatomy of a CARISMA site



CARISMA site examples

Core site at Rankin Inlet, NU

CFI site at Gull Lake, SK

NGEN site at Prince Albert, SK

UNIVERSITY OF ALBERTA

Field Operations: Why is the data missing?

- Instrument failure
  - Electronics
  - Lightning
  - Physical damage
- Infrastructure
  - Extended power outage
  - UPS failure
  - Data logger failure
- Repair?
  - Diagnosis: Remote + local help
  - Ship spare parts to core sites
  - Travel (priority scheduling)

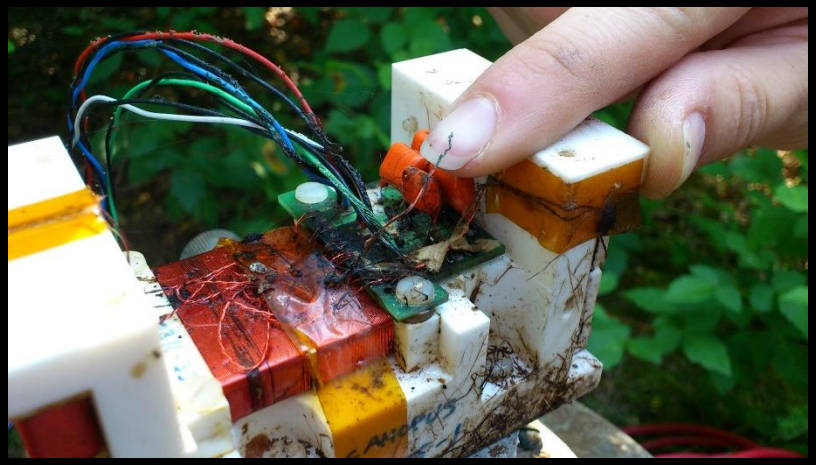
Sensor Damage

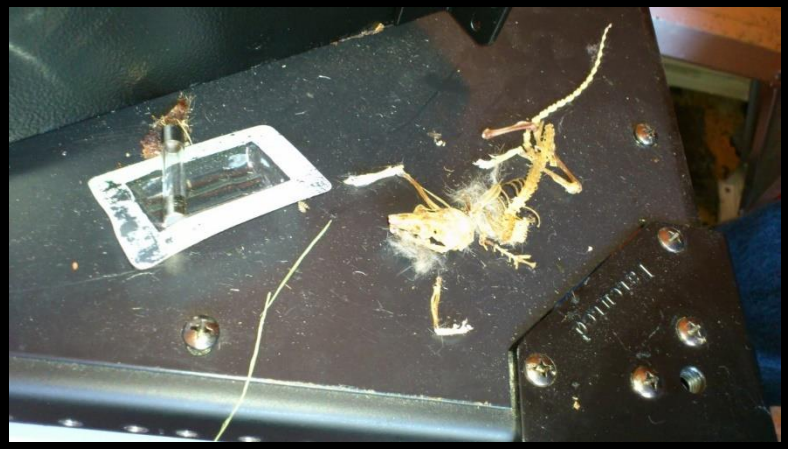
Bear incident at Wells Gray

Digger incident at Weyburn

UNIVERSITY OF ALBERTA

Mouse attack





Wildfire at Prince Albert

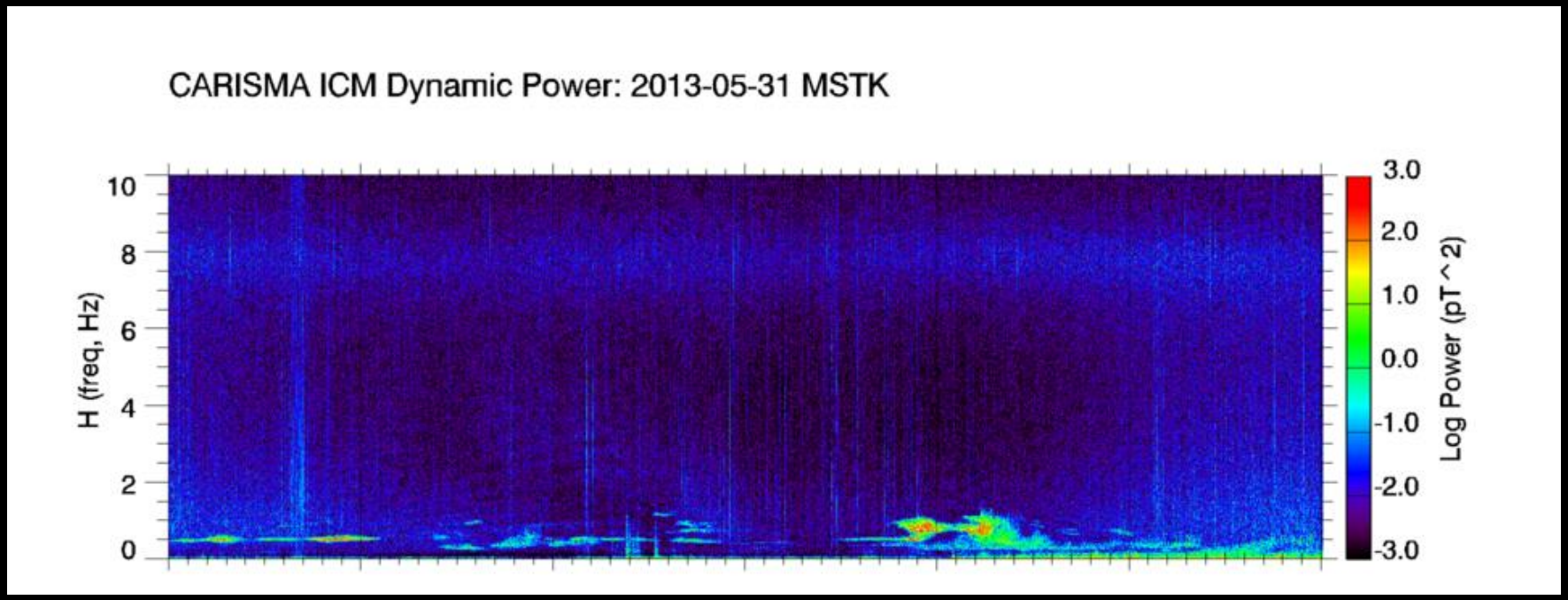
UNIVERSITY OF ALBERTA

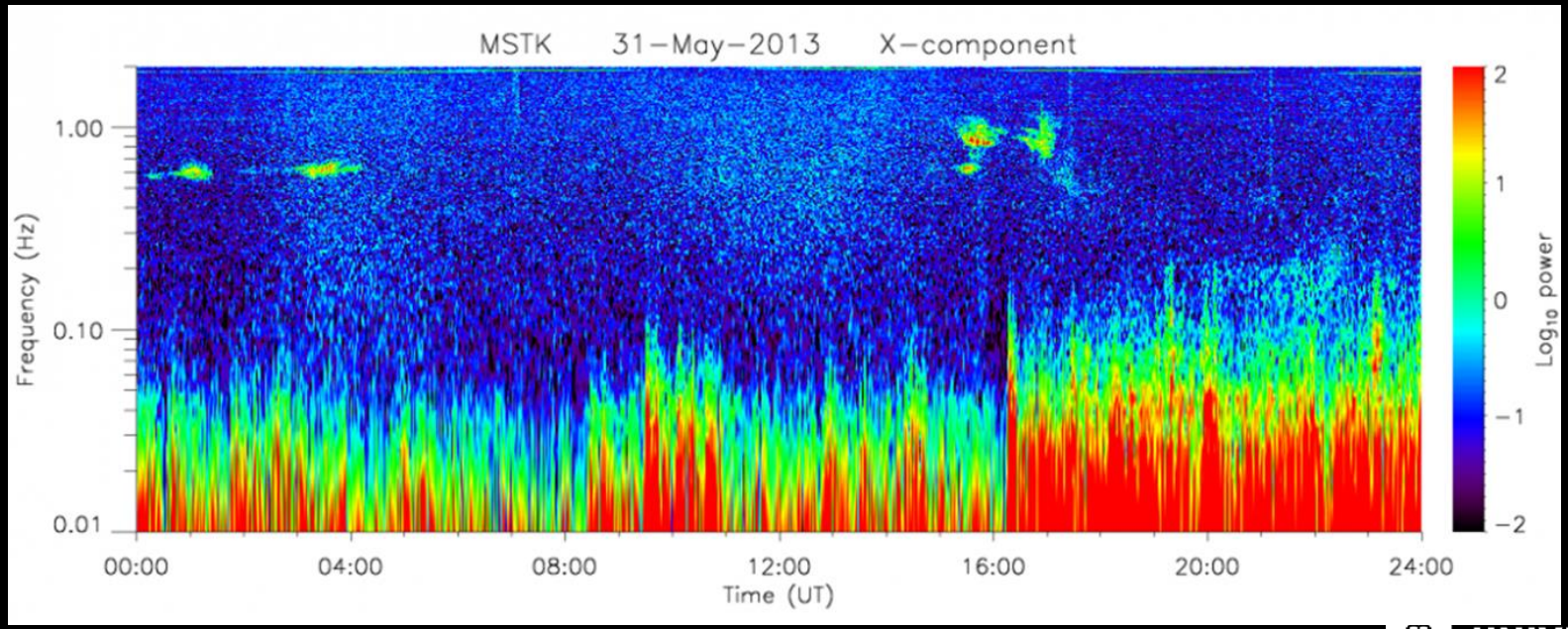
Pier tilting at Rankin Inlet, NU

UNIVERSITY OF ALBERTA

Noise Sources

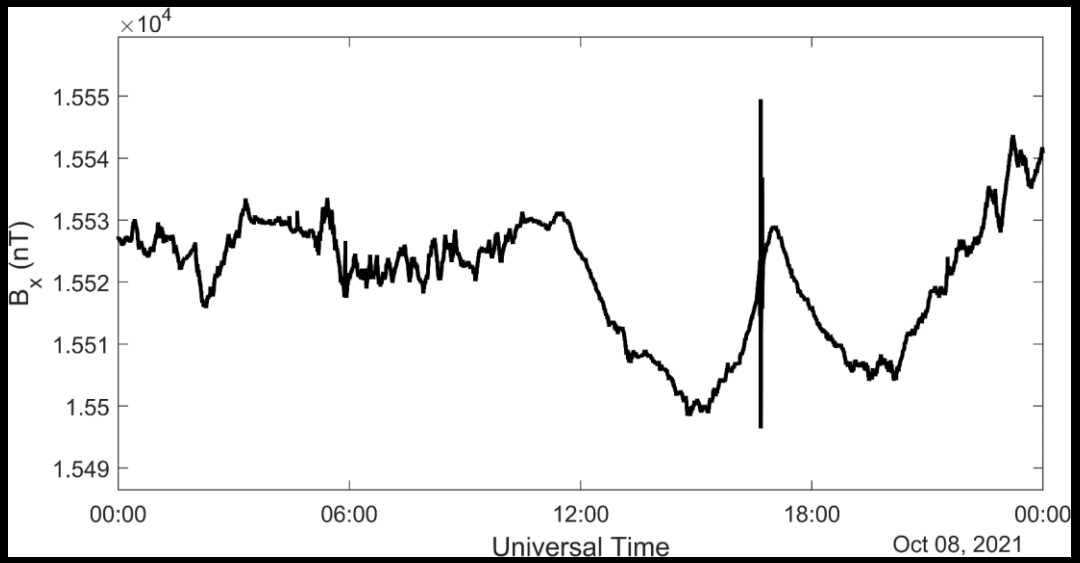
- Instrument
  - designed to be low noise compared to measured signals
- Local Industry
  - E.g Hydro generating plant at Gillam; High frequency noise + current dumps
- Local activity – vehicle movement; people;

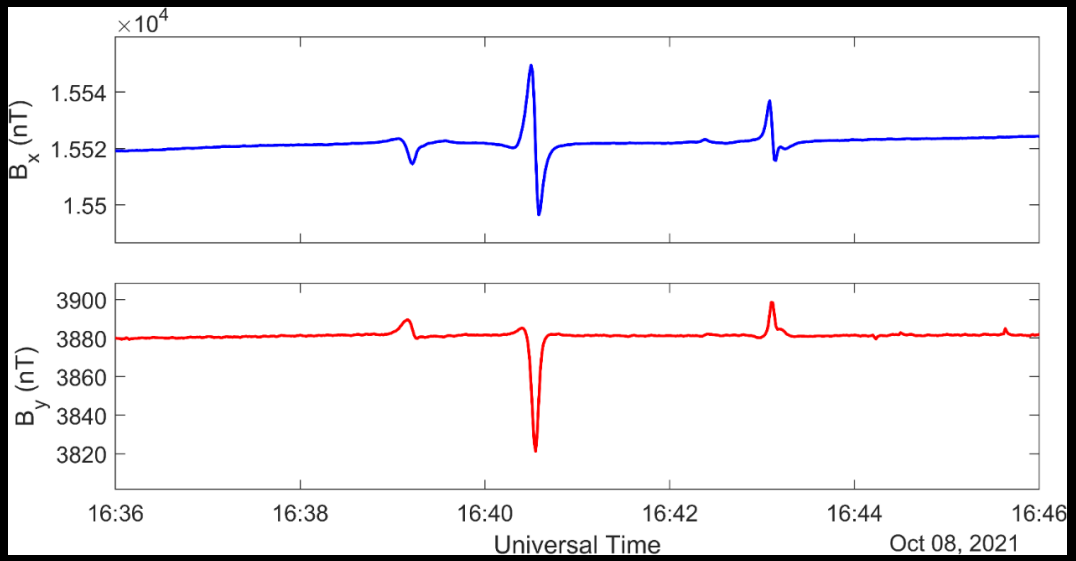




UNIVERSITY OF ALBERTA

Local Noise: Vehicle Movement

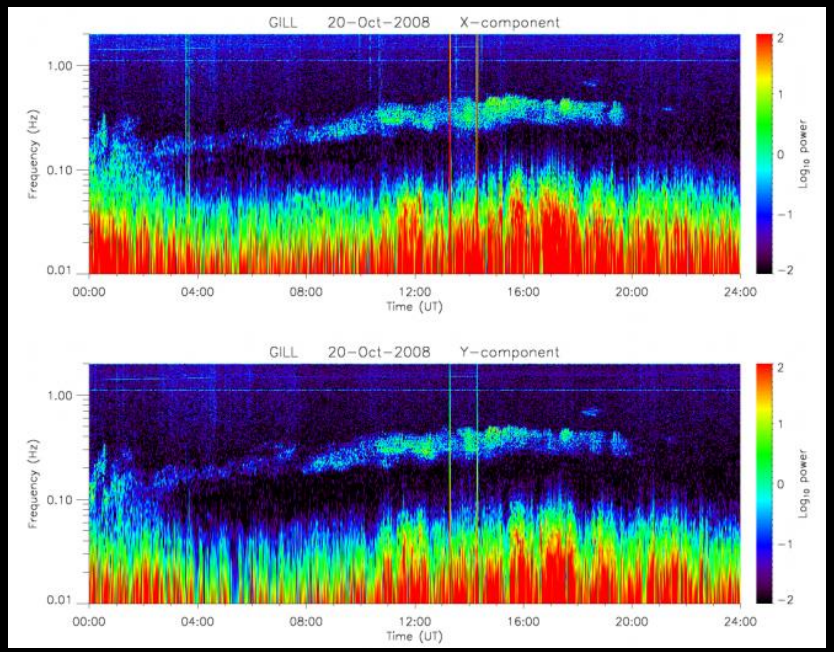




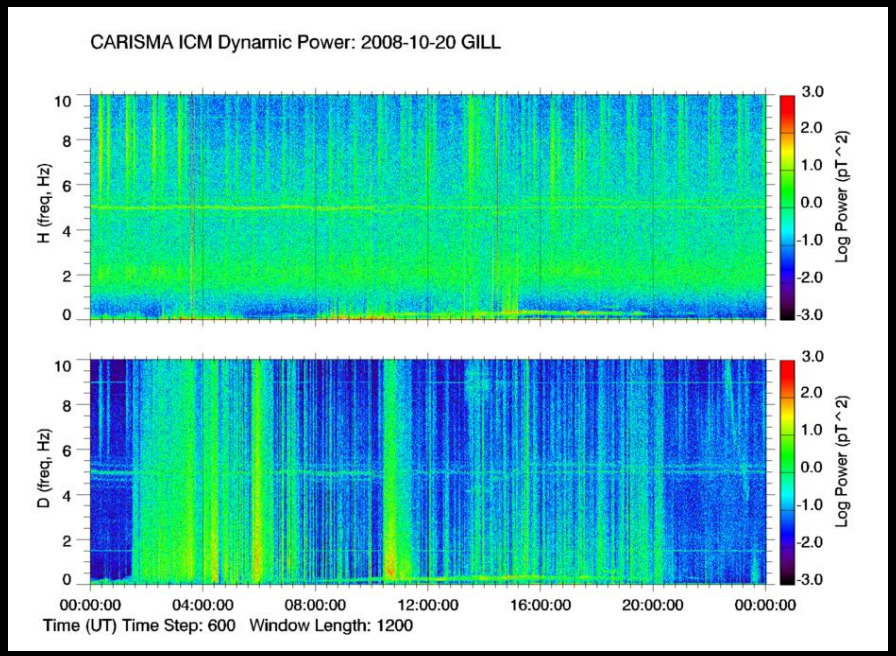
From: Hannah Parry

UNIVERSITY OF ALBERTA

Noise at Gillam due to 1.2 GW Kettle Generating Station



FGM Data



ICM Data

UNIVERSITY OF ALBERTA

Data Products

- Data is available directly from

  data.carisma.ca/FGM

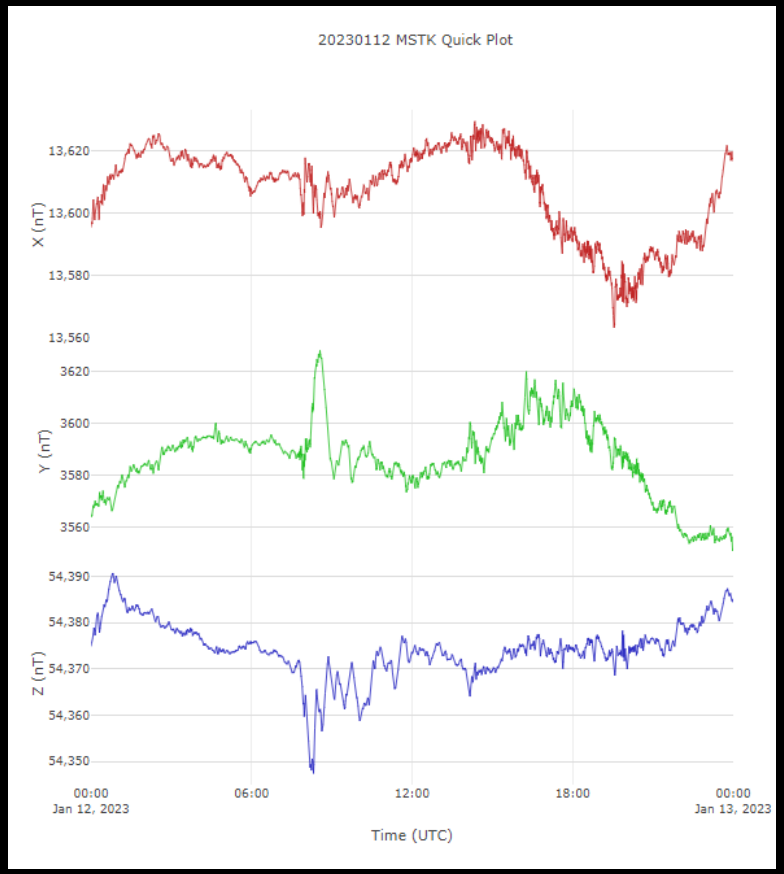
  data.carisma.ca/ICM
- More graphical data products from carisma.ca
  - Magnetograms
  - Dynamic Spectra
  - Pi2 database
  - Canadian Auroral Indices

- Kyle Murphy will talk later about data use and GMAG

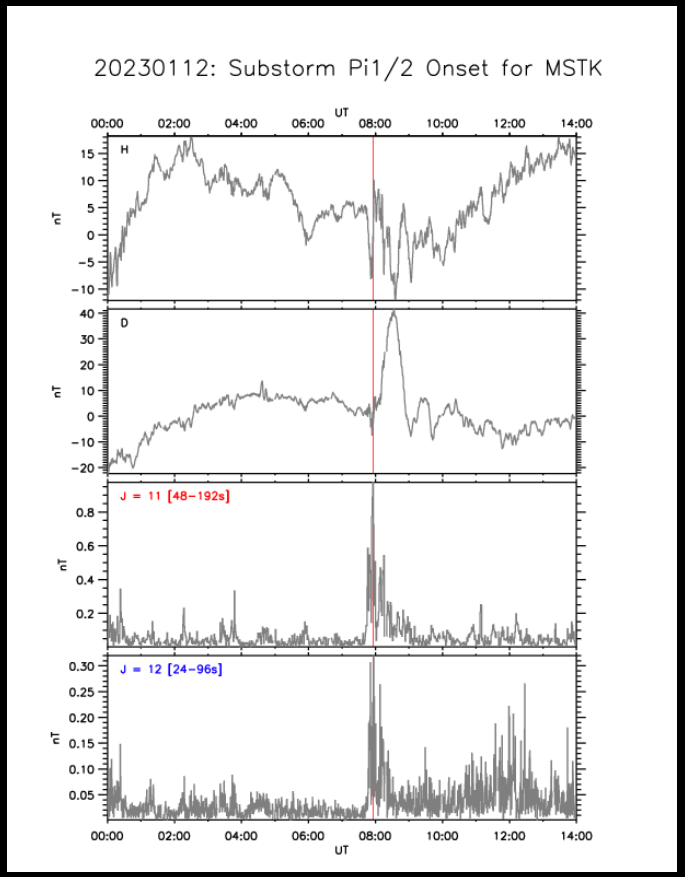
What does CARISMA measure?

- FGM
  - Ionospheric and magnetospheric currents
  - Geomagnetic storms and substorms
  - ULF waves (Pc5 – Pc1)
  - Remote sensing Plasma Density (cross-phase)
  - Rad Belt dynamics via ULF wave power
- ICM
  - EMIC waves
  - Schumann resonances
  - IAR

Substorm Timing using Pi2



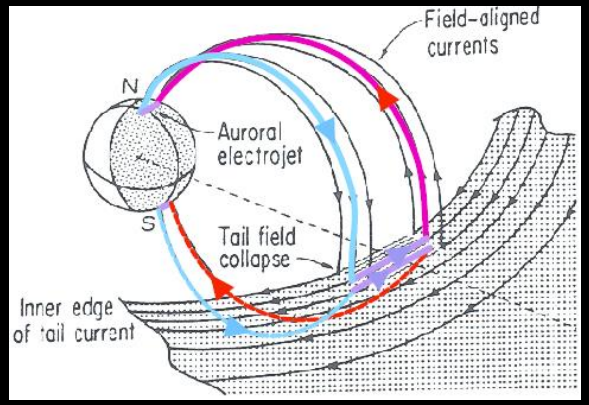
FGM Quick Plot

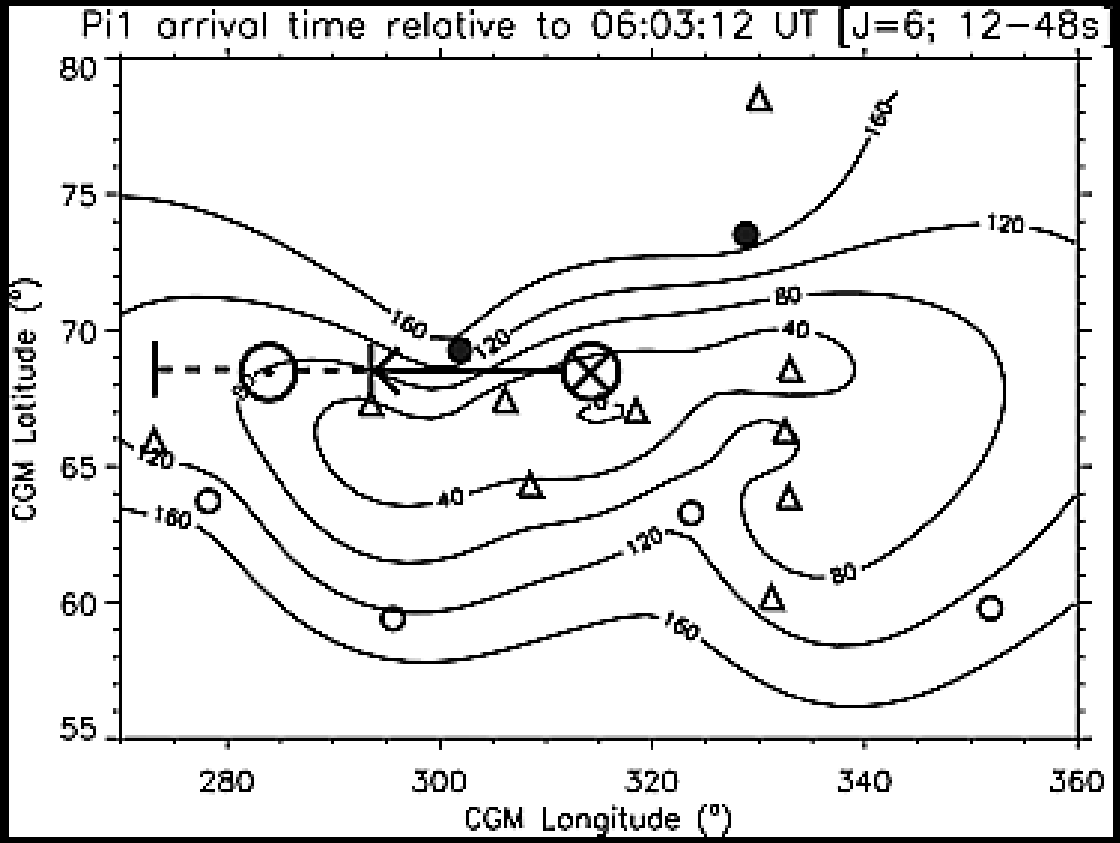


Pi2 Database

UNIVERSITY OF ALBERTA

Substorm Location using Bays and Pi1



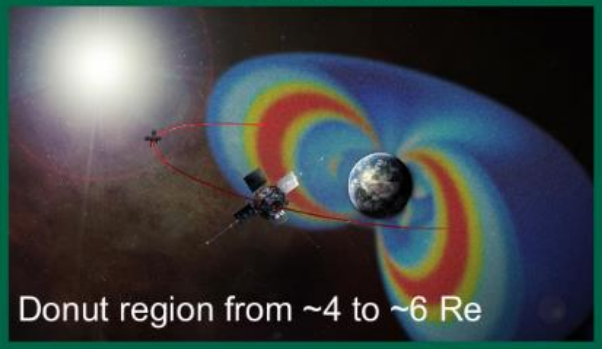


Milling et al, 2008

UNIVERSITY OF ALBERTA

Modeling the Radiation Belts with CARISMA Data

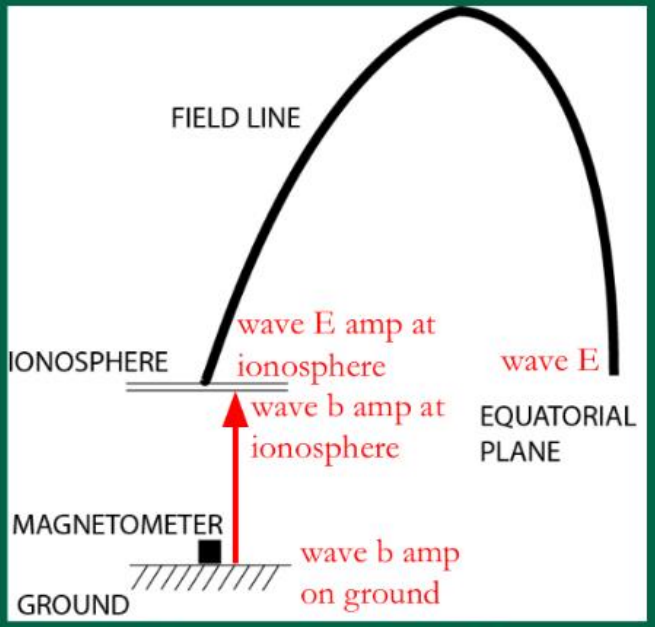
The Earth's Outer Radiation Belt



The dynamics of the outer belt are controlled by the global ULF wave electric field power in space

CARISMA sites below the Outer Belt

The ULF wave power on the ground can be measured using FGM networks such as CARISMA

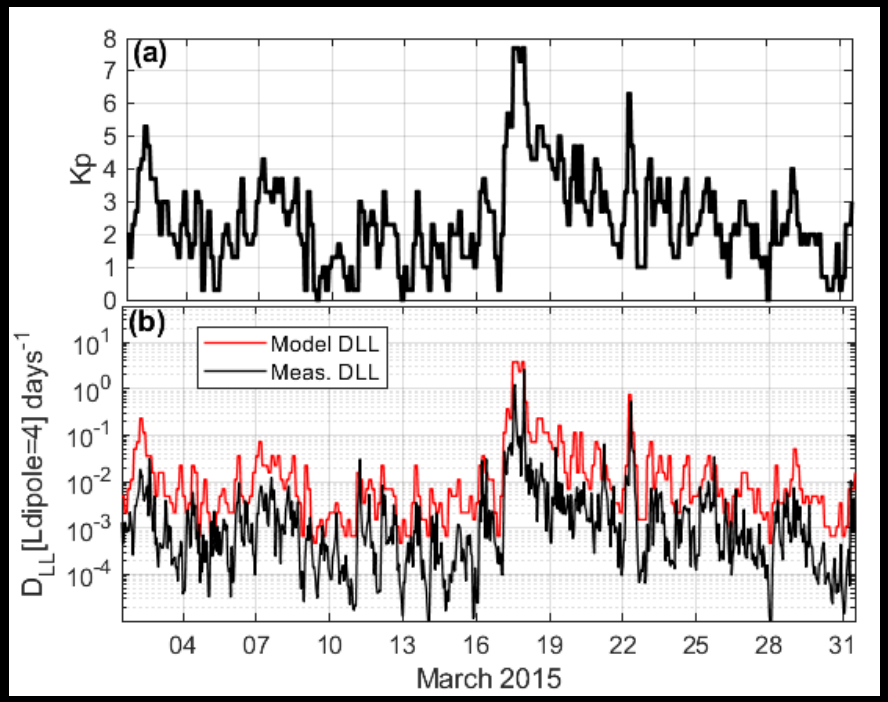


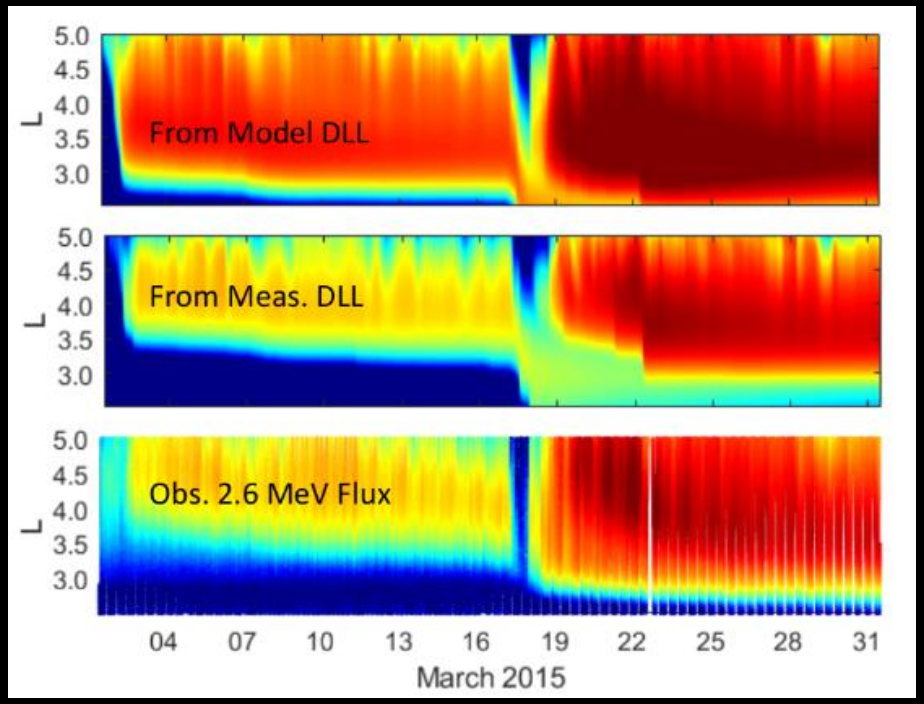
The ULF wave electric field power in space needed to model the outer belt can be estimated using the ground FGM measurements;
Ozeke et al., 2009,
Mann et al., Nature, 2016.

From: Louis Ozeke

UNIVERSITY OF ALBERTA

DLL model driven by Kp index compared with DLL derived from measured ULF wave power

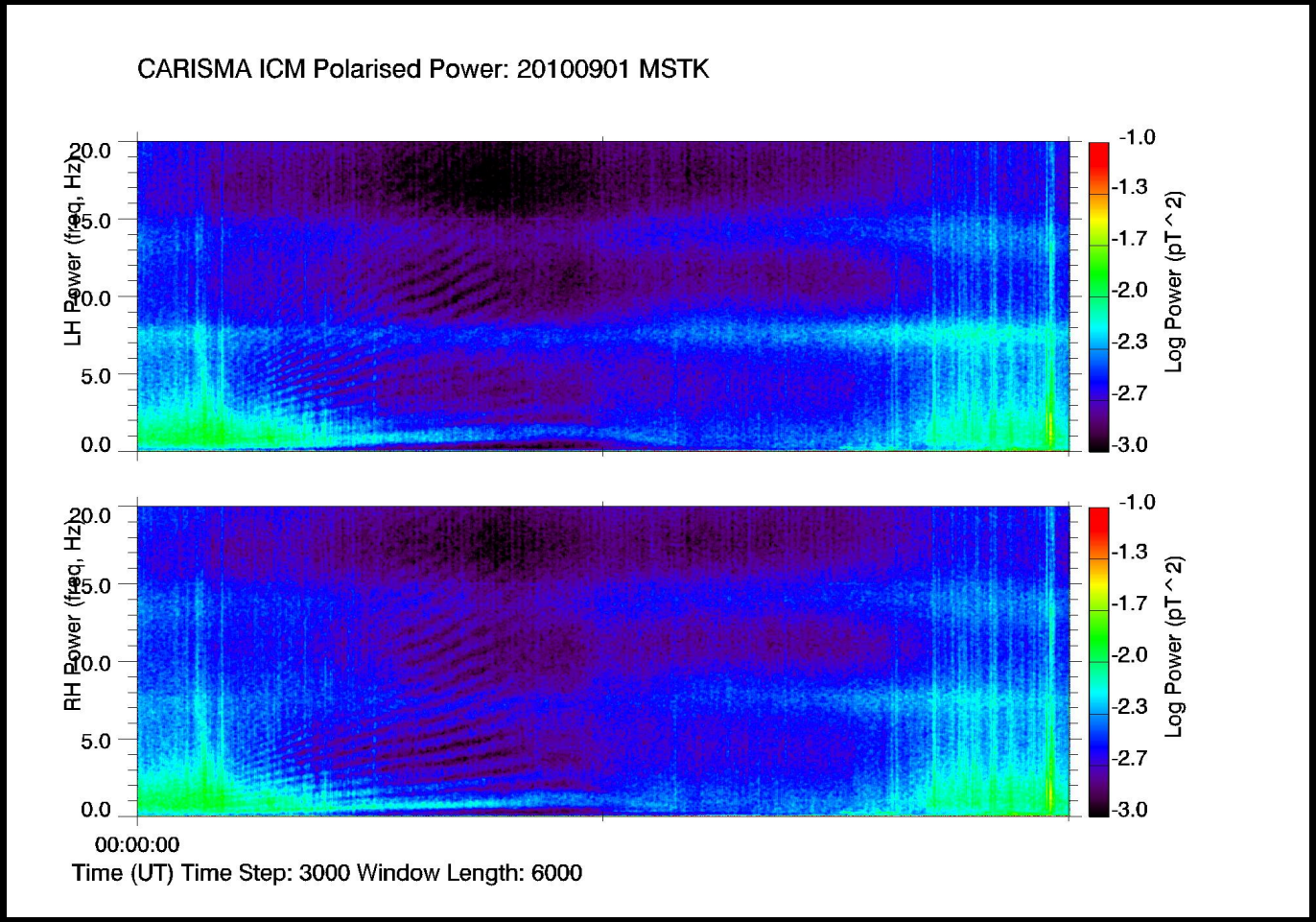




From: Louis Ozeke

UNIVERSITY OF ALBERTA

ICM Signals: IAR and Schumann



UNIVERSITY OF ALBERTA

Thank you!

- This program is undertaken with the financial support of the Canadian Space Agency.

Canadian Space Agency

Agence spatiale canadienne

UNIVERSITY OF ALBERTA