Personal Space Weather Station

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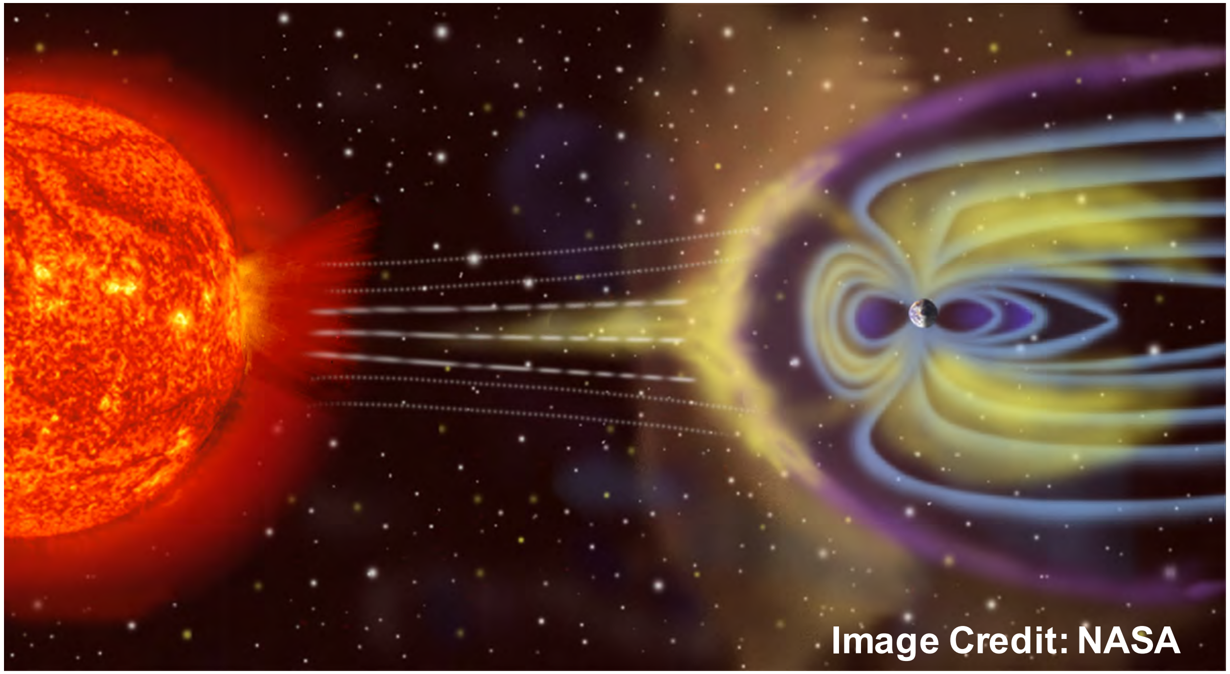
What is Space Weather?

- Space weather is *broad* field, covering solar, heliospheric, magnetospheric, ionospheric physics, meteorology, aerospace engineering, etc...
- Definition: “Space weather refers to conditions on the Sun and in the space environment that can influence the performance and reliability of space-borne and ground- based technological systems, and can endanger human life or health.”

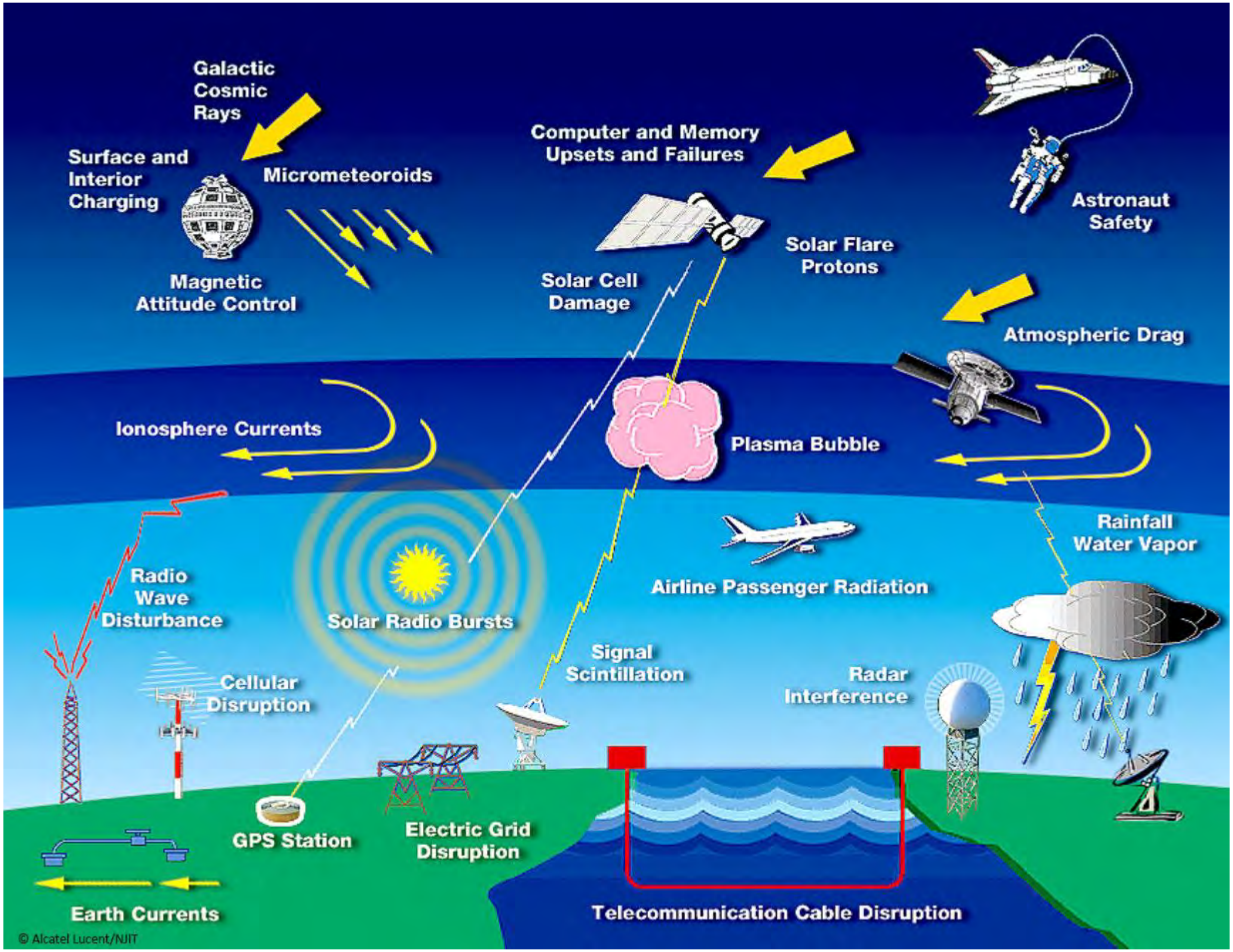
[National Space Weather Program]

Where is Space Weather?

- Sun (Heliosphere)
- Solar Wind
- Magnetosphere
- Ionosphere



What does Space Weather affect?



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But… Space Weather? Or Climate?

- We talk about Space Weather all of the time.
- But really, we have some understanding of space climate, not space weather.
- Climate example:
  - 11 Year Solar Cycle
  - Ionosphere Day/Night Cycle
  - Seasonal variations in propagation
- Weather example
  - Solar flares
  - Geomagnetic storms

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Space Weather Station Goals

As hams building a Personal SW Station, what do we want to do?

Operations

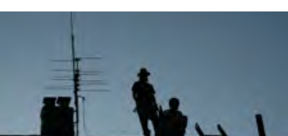
Hams:

- Know the best frequencies for working DX
- Understand the RFI Environment
- Communicate better during emergencies

Research

Scientists:

- Better sample the environment
- Better understand near-Earth Space

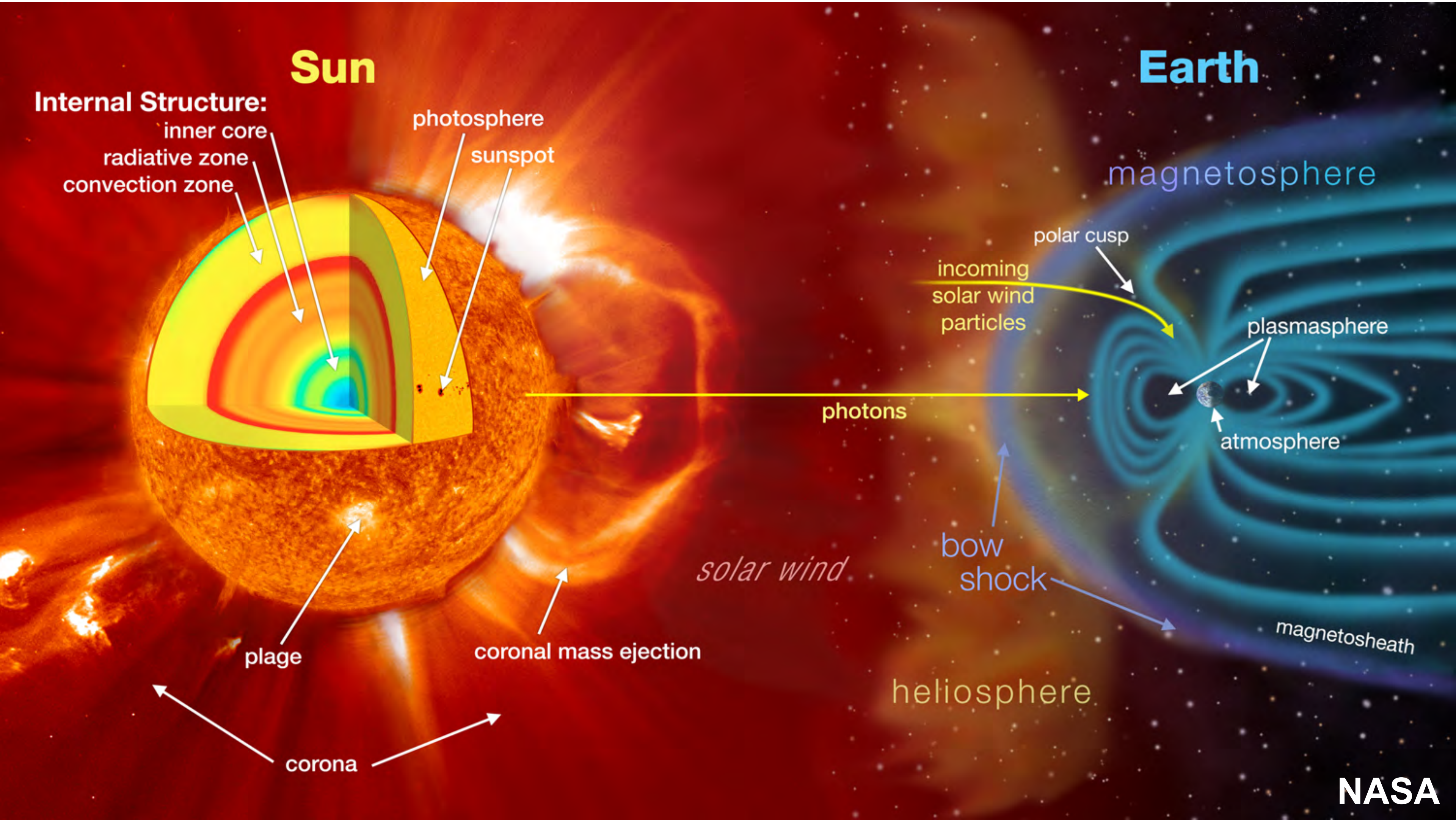


Outline

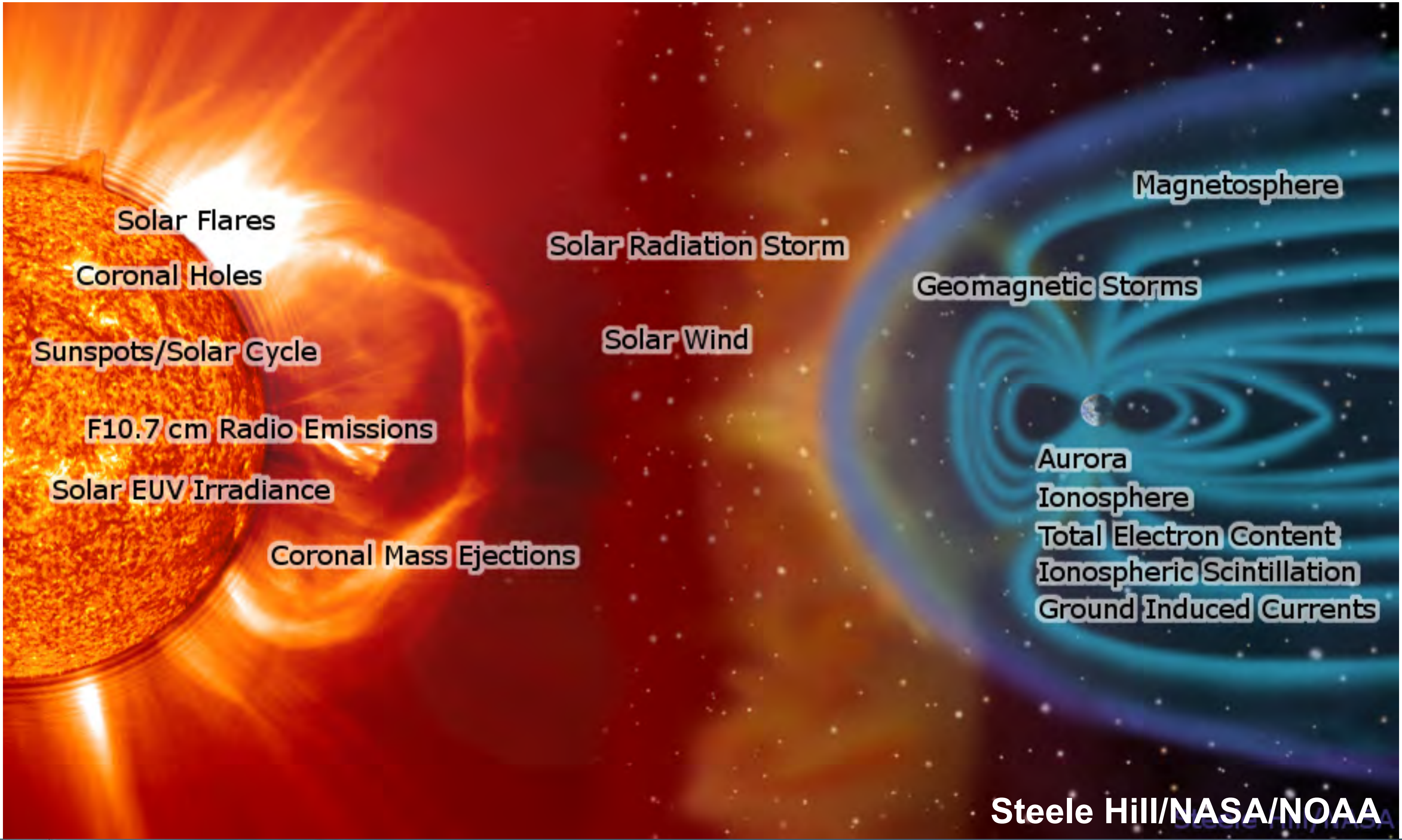
I. The Space Environment
II. Traveling Ionospheric Disturbances
III. My Vision of a Personal Space Weather Station
IV. HF Receiver Instrument
V. Project Goals and Timeline

The Space Environment

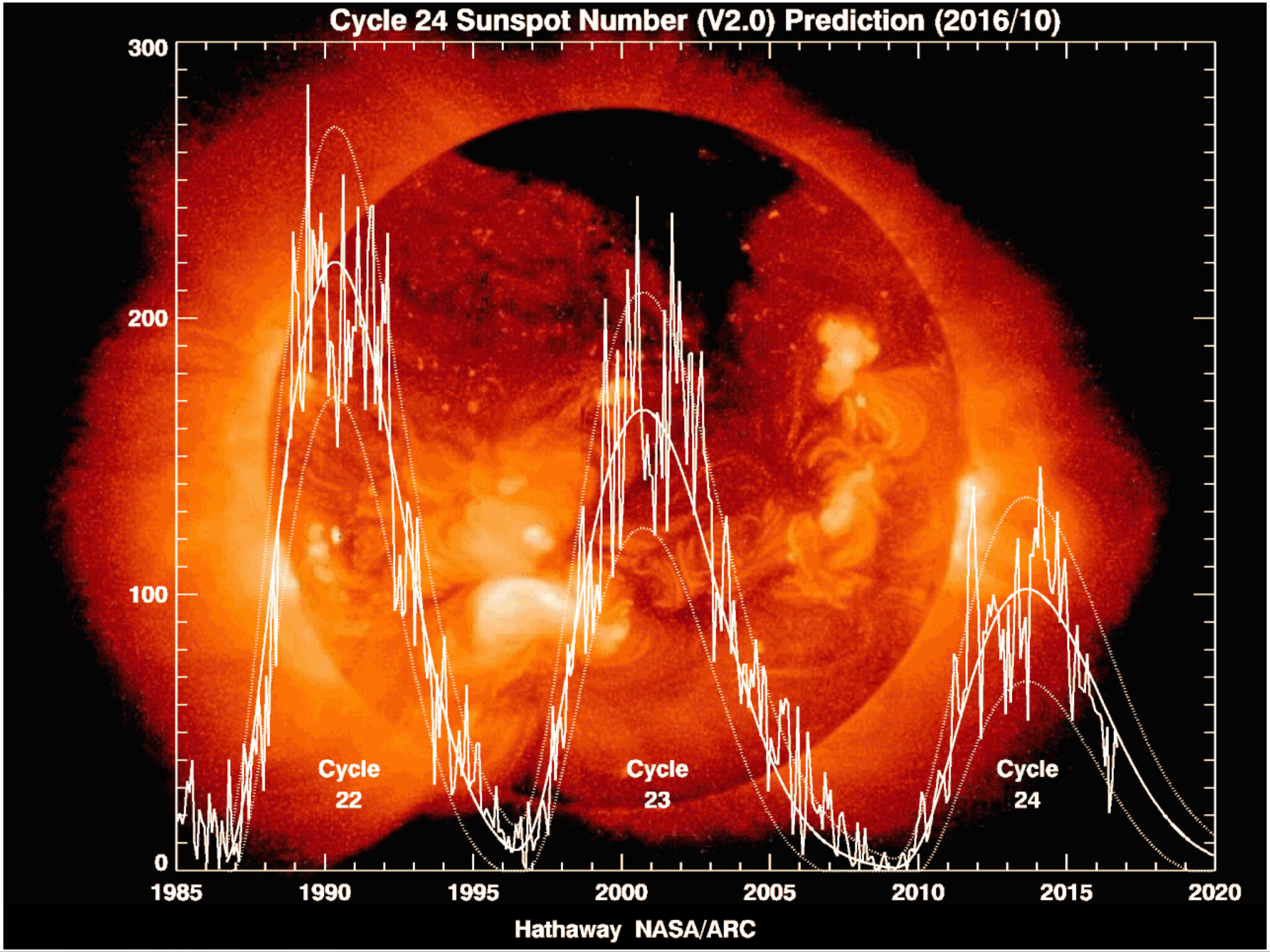
Solar-Terrestrial Environment



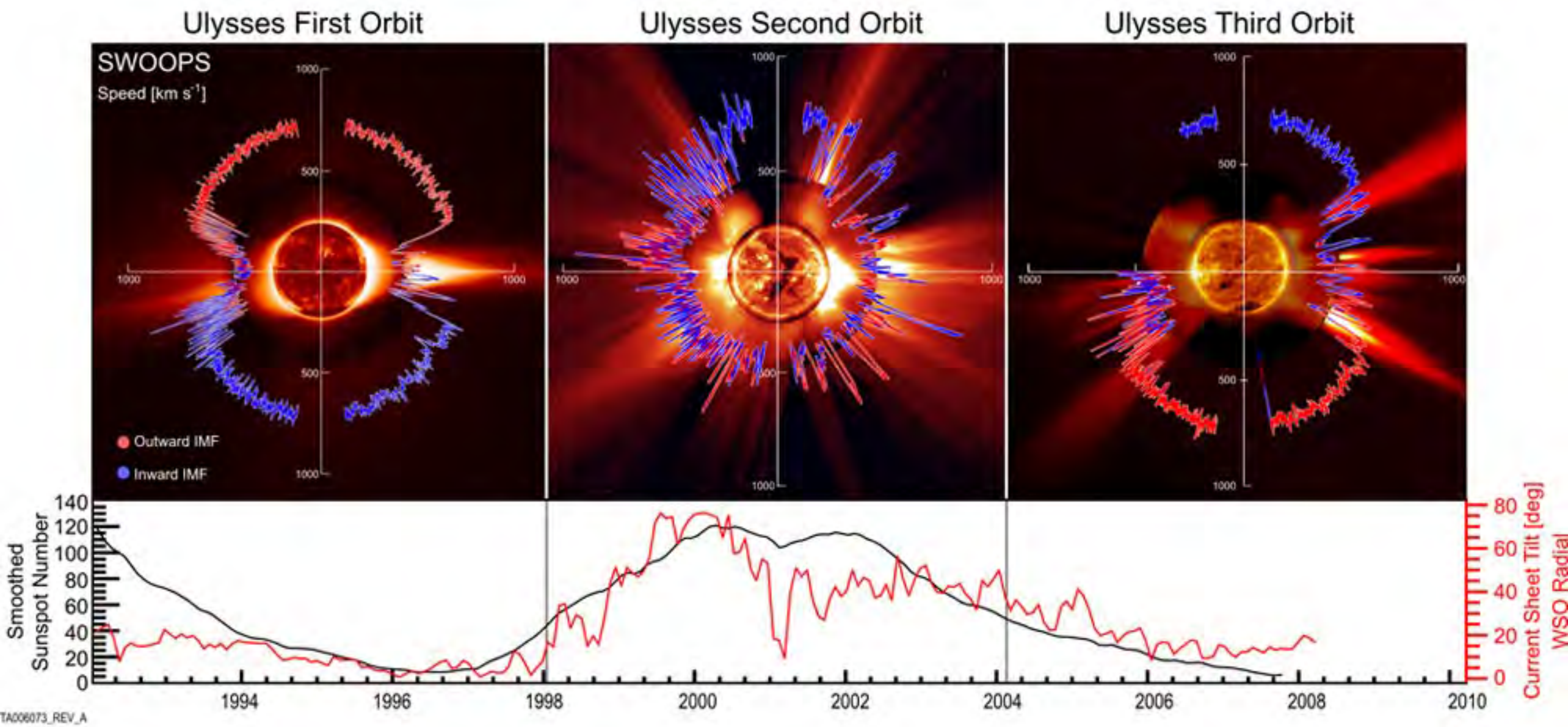
Solar-Terrestrial Environment



Sunspot Cycle



Solar Wind Over a Solar Cycle

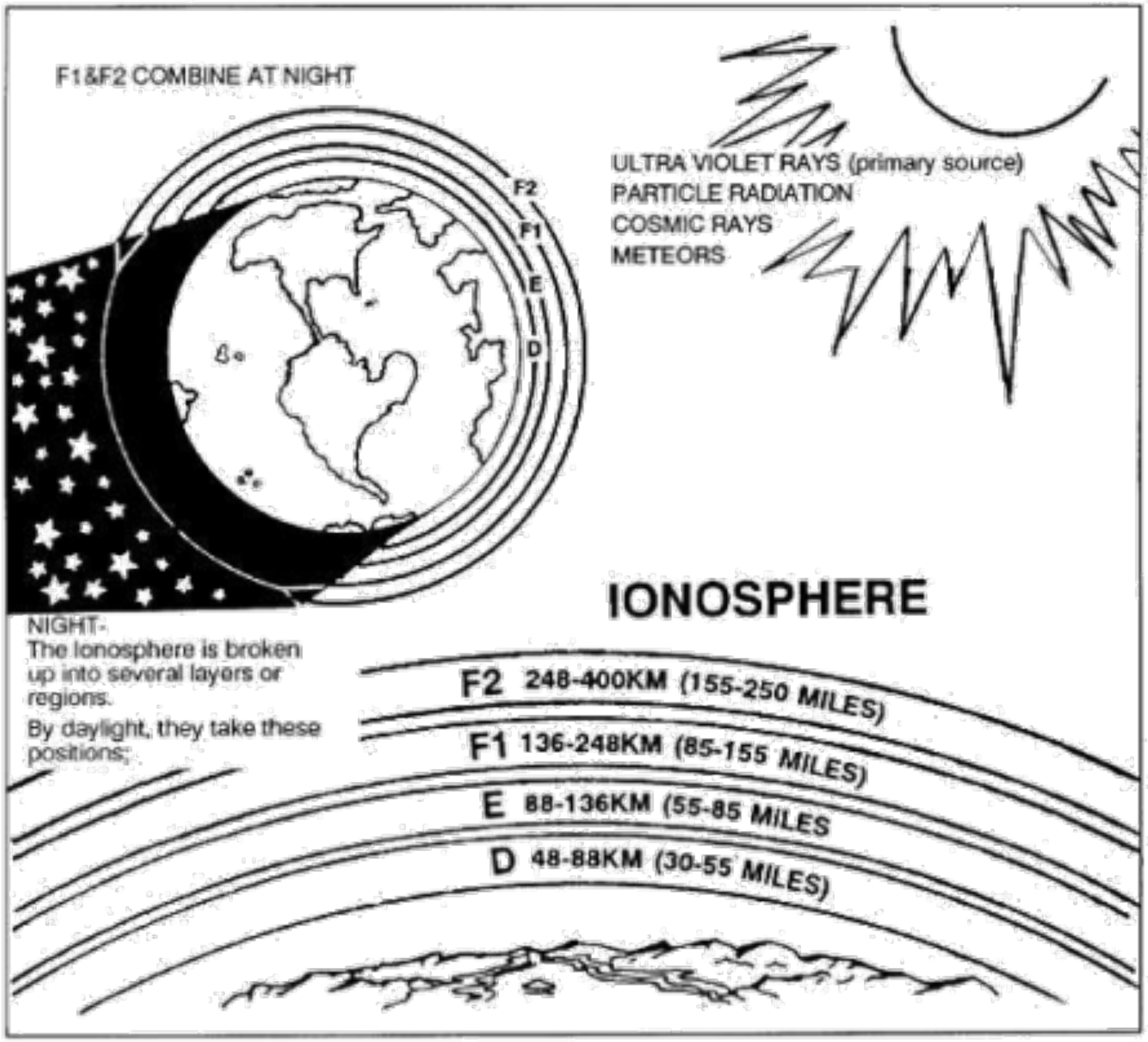


[McCommas et al., 2008, doi:10.1029/2008GL034896]

Differential Rotation

[NASA]

Ionosphere



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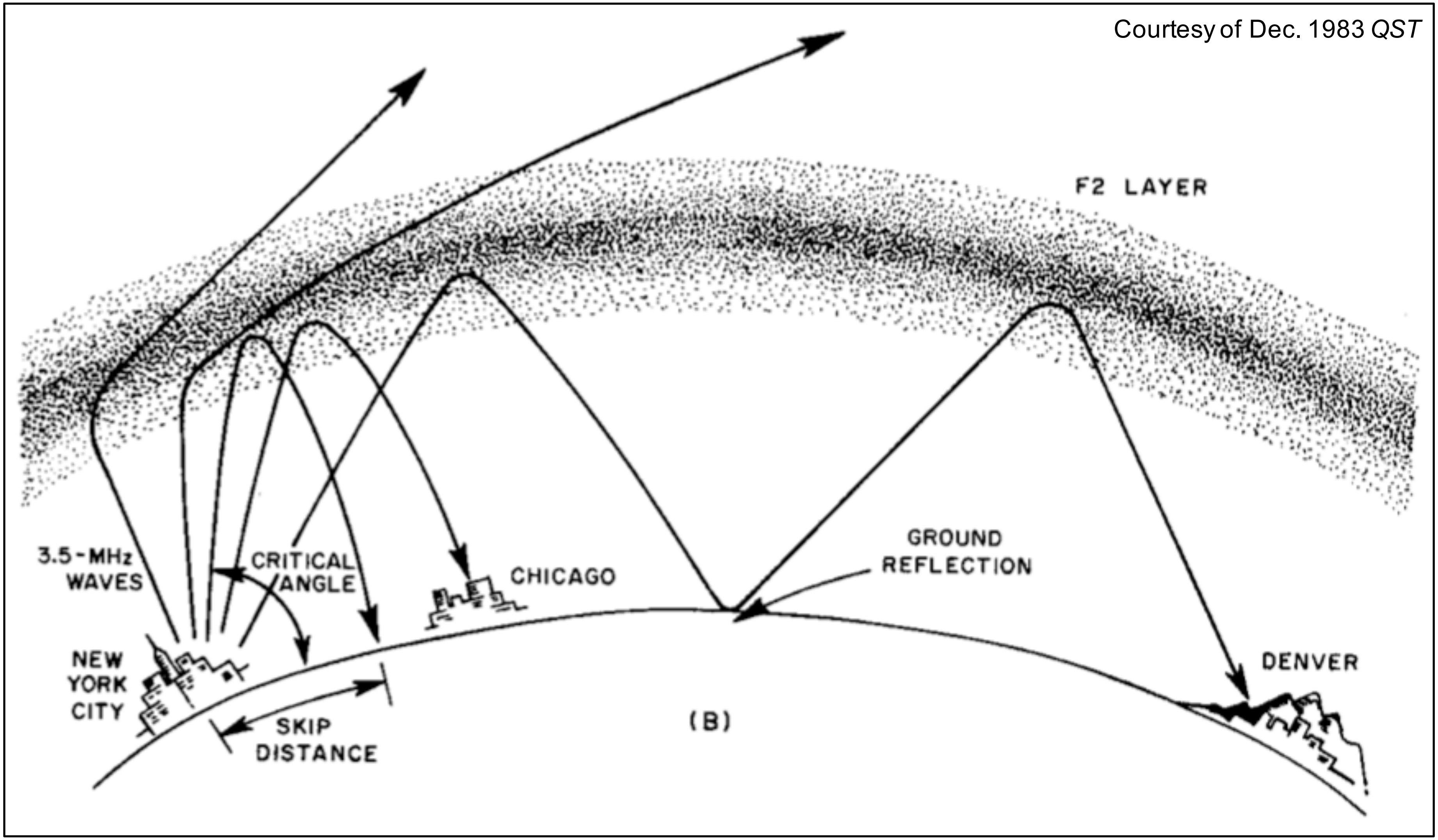
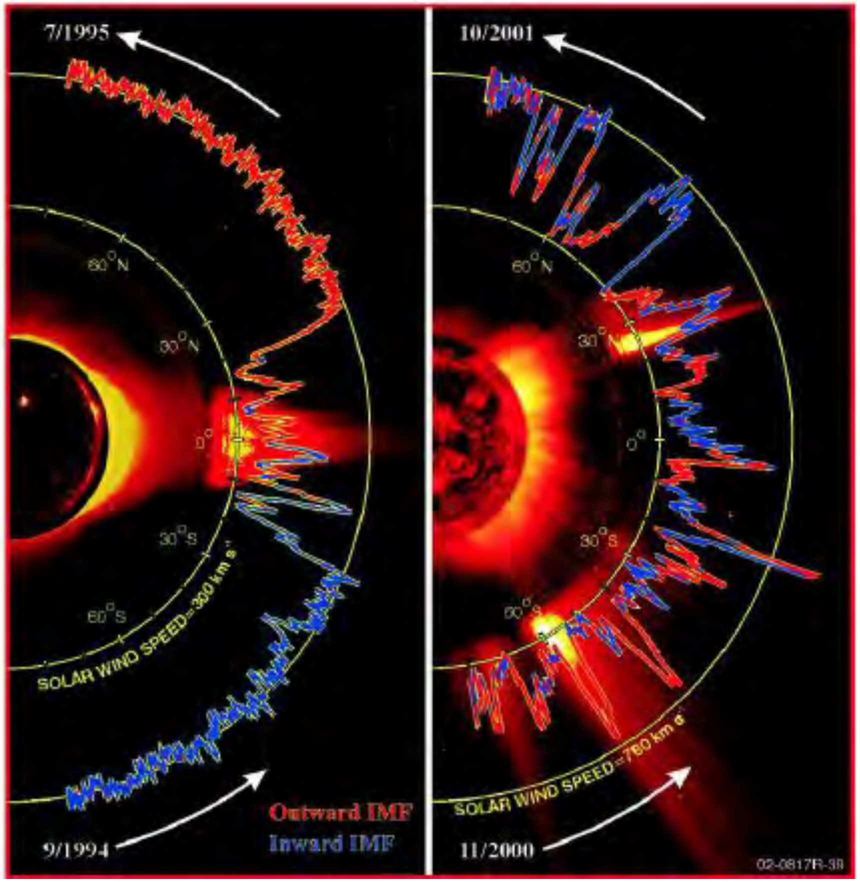
Skip Propagation



Solar Wind & IMF

- Travel time to Earth: 2 to 4 days
- Magnetic field vector varies in magnitude & direction (~5 nT)
- Velocity: 300 to 800 km/s
- Density: 3 to 50 cm^{-3}
- Temperature: ~10^5 K

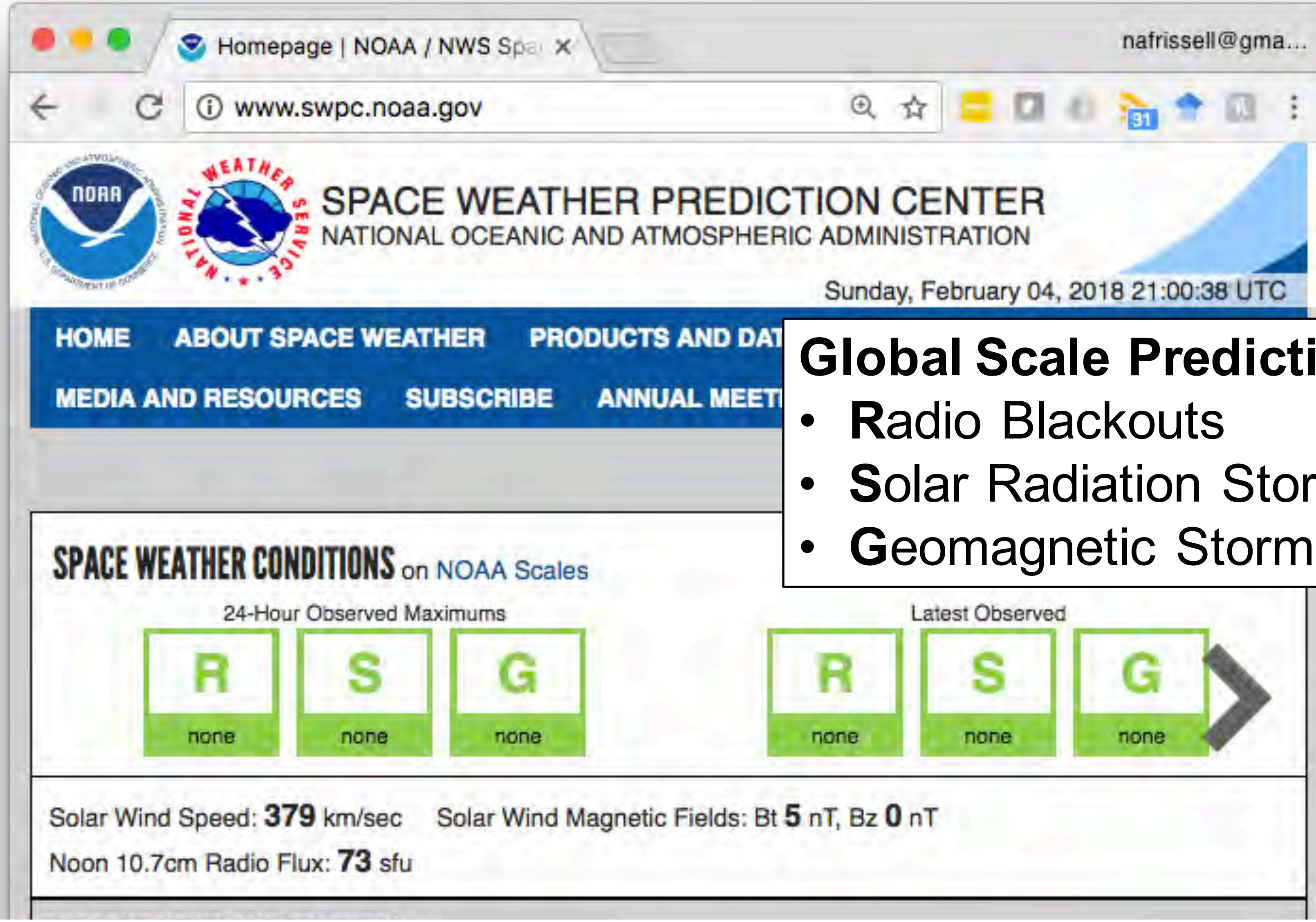


[de Castro, 2008, doi:10.1007/s10509-008-9894-4]

Sun Facts

- The 11-year cycle is really a 22-year cycle (taking polarity flip into account)
- Total solar luminosity (dominated by visible light) varies only by ~0.1%
- Emission in UV & X-rays varies by orders of magnitude over the cycle.
- Sunspots
  - Regions of strong magnetic field
  - Dark because they are cool

NOAA Space Weather Prediction Center

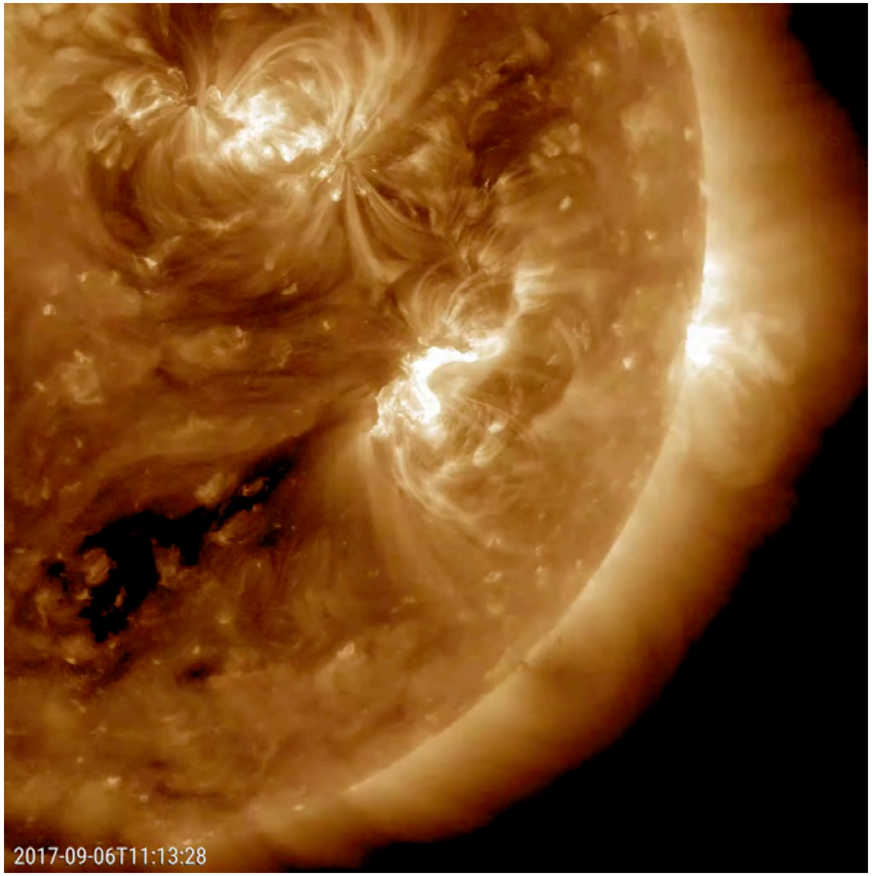


Global Scale Predictions

- **R**adio Blackouts
- **S**olar Radiation Storms
- **G**eomagnetic Storms

Solar Flares

- Sudden increase in electromagnetic energy from localized regions on the sun.
- Energy travels at the speed of light (8 min to Earth)
- Soft X-Ray (0.1-0.8 nm) Earthward-directed energy can cause HF radio blackouts.
- Often, but not always, accompanied by a CME.



NASA SDO Observation of X9.3 Solar Flare on Sept 6, 2017

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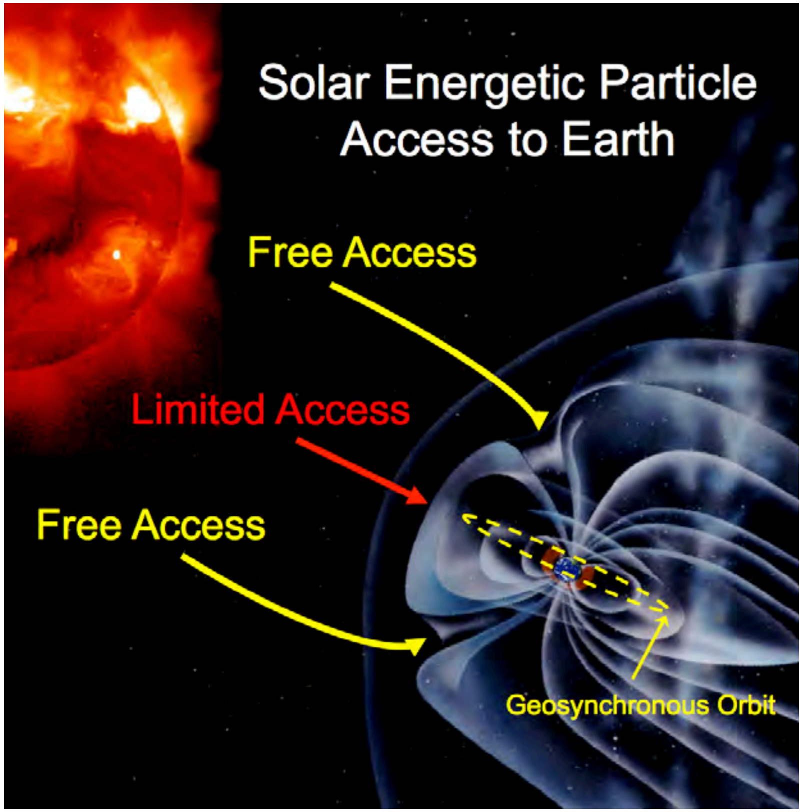
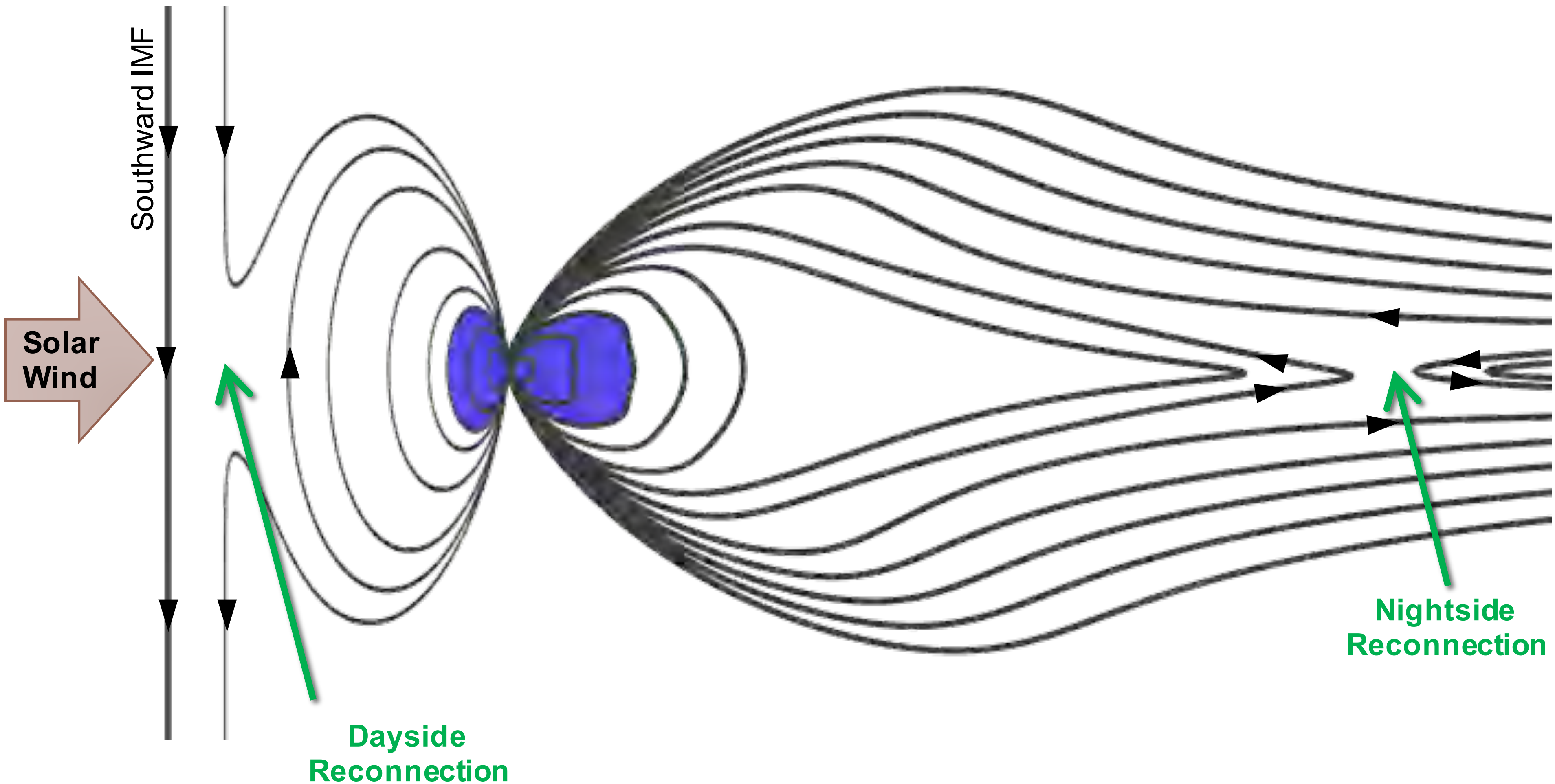
Solar Radiation Storm

- Large-scale magnetic eruption on the sun accelerates charged particles to very high velocities.
- Associated with CMEs or Solar Flares
- Accelerated protons are most important
  - 1/3 speed of light (100,000 km/s)
  - 15 min to hours to reach Earth
- Guided by field lines into polar regions.
- Lasts for hours to days



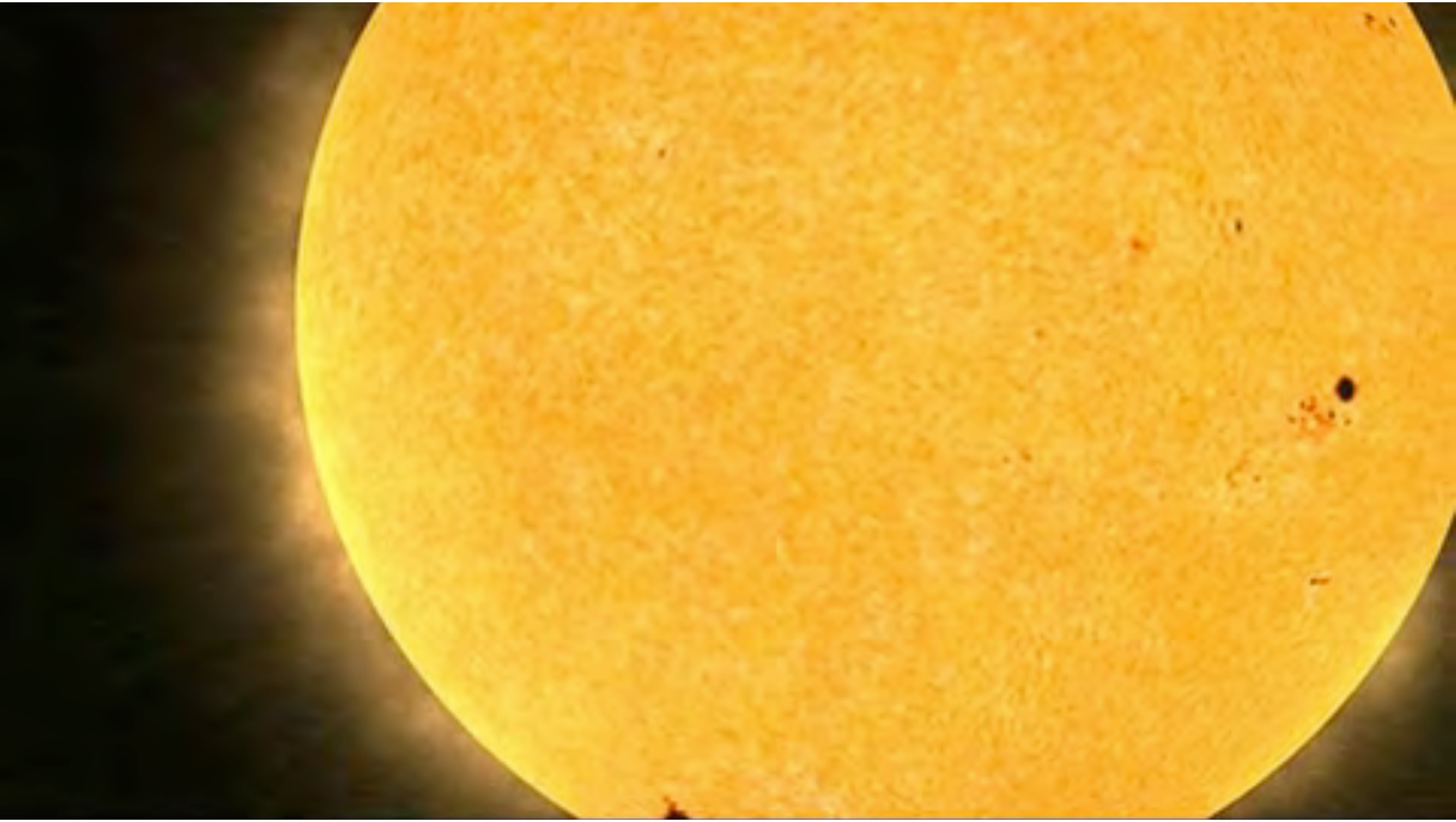
[NASA / Annotated by H. Singer]

Getting Energy into the Magnetosphere



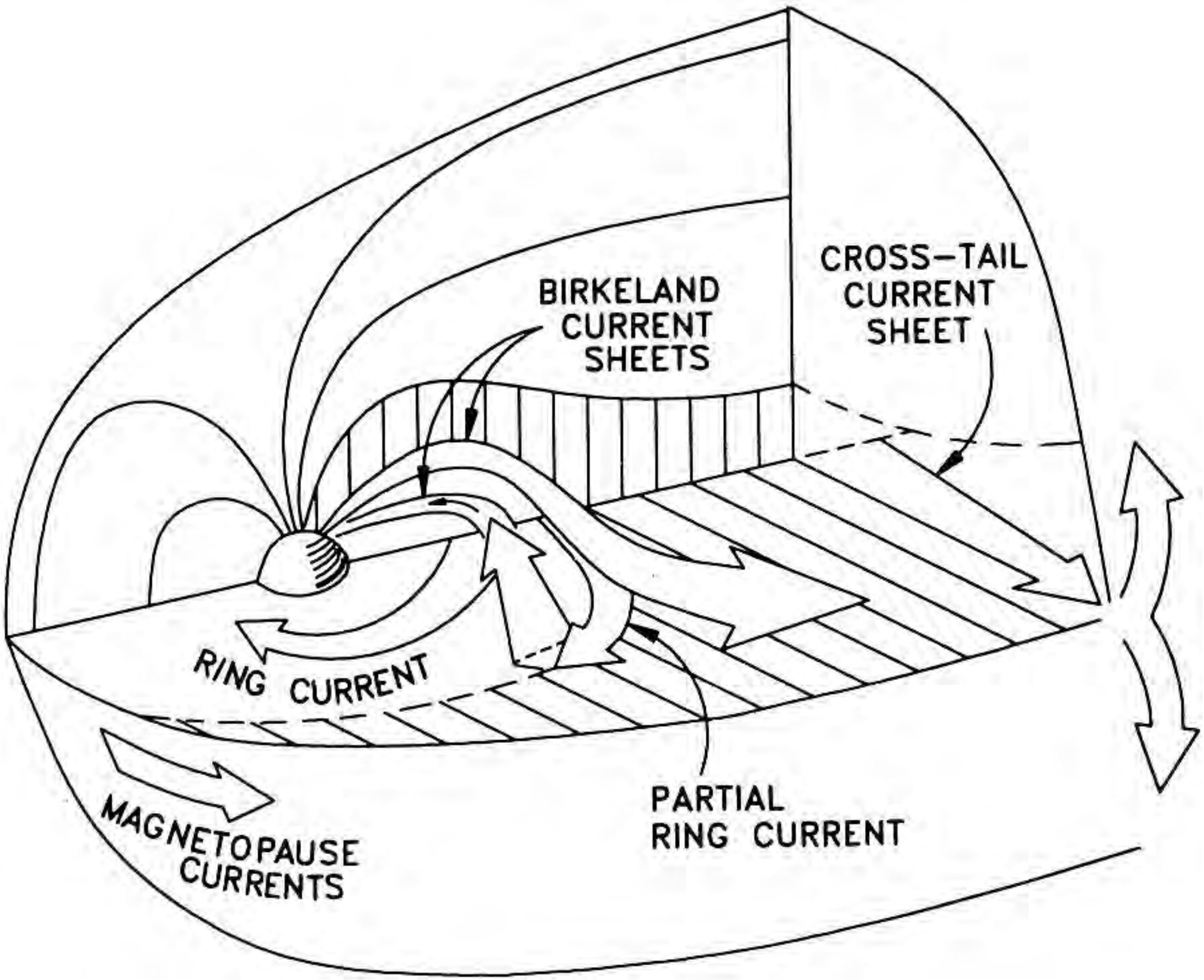
[Frissell, 2016, Dissertation]

Substorms



[Visualization by NASA]

Magnetospheric Current Systems

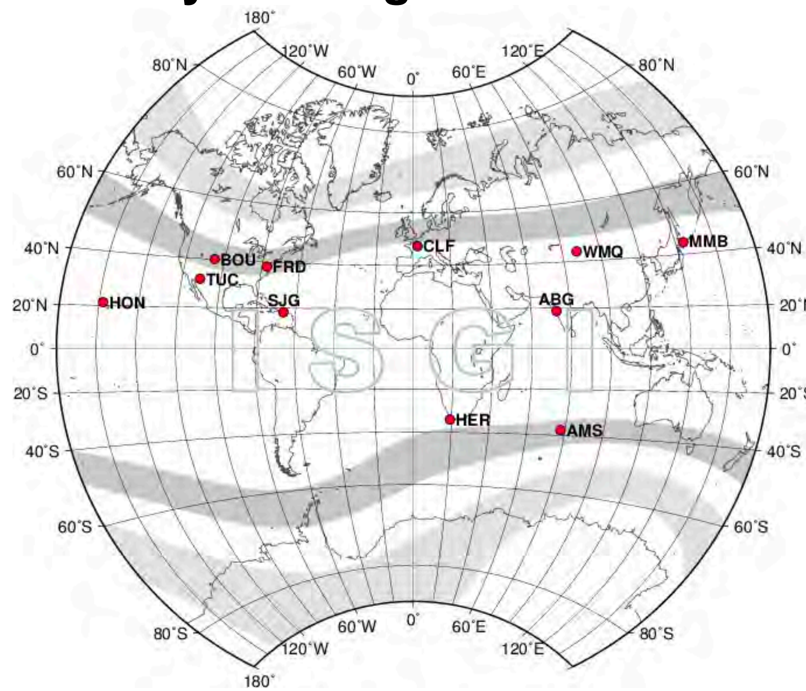


[Stern, 1994, doi:10.1029/94JA01239]

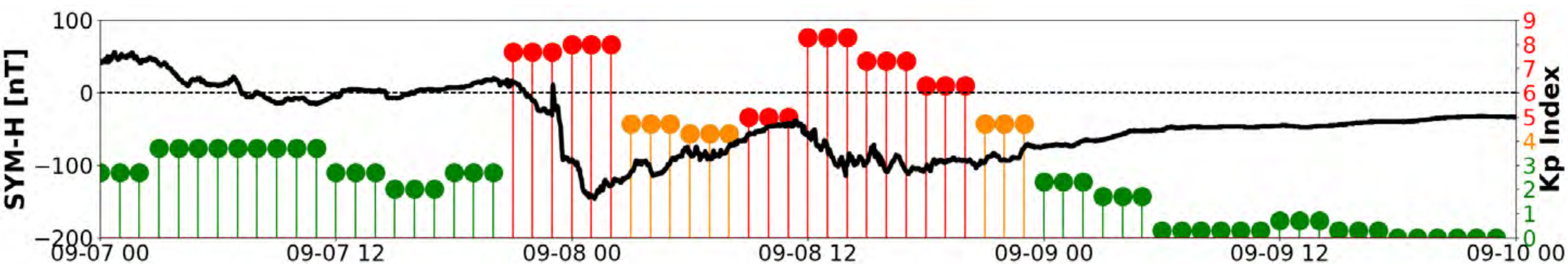
Geomagnetic Storms

- Fast CMEs and CIR/HSSs can lead to geomagnetic storms.
- Requires efficient energy exchange between solar wind and magnetosphere (extended periods of southward Bz and high-speed solar wind).
- Defined by negative excursion in Dst/Sym-H indices.

Sym-H Magnetometers

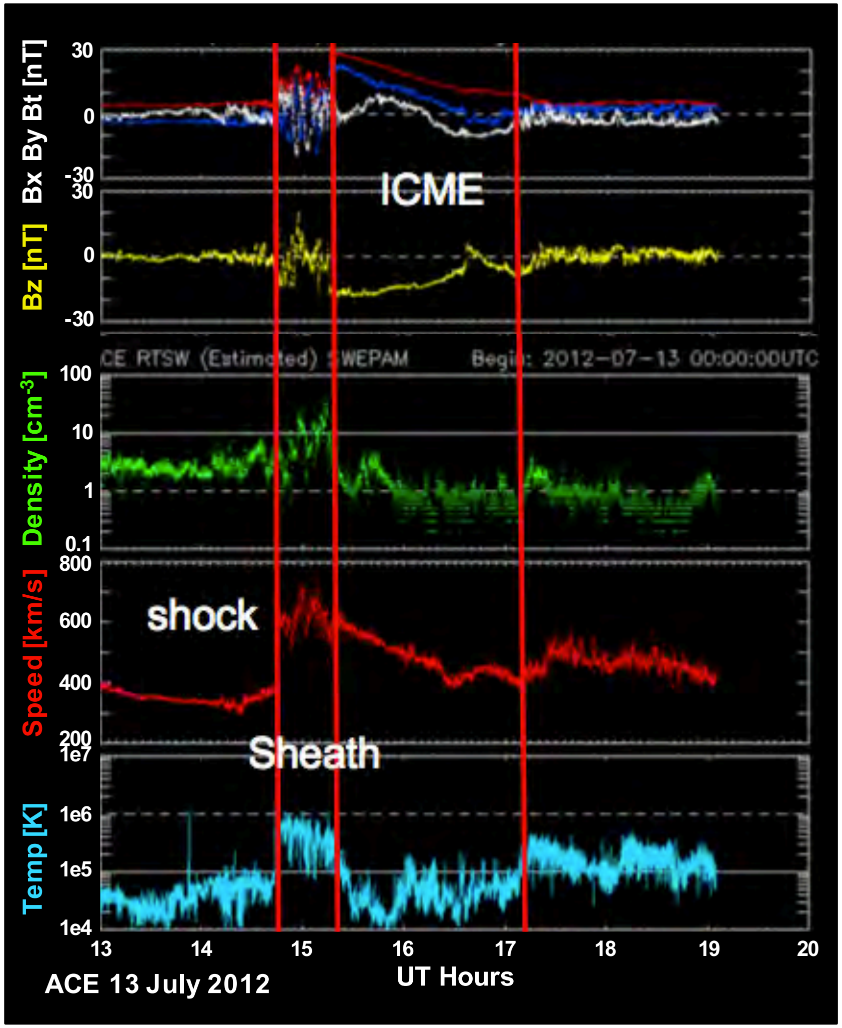


http://isgi.unistra.fr/indices_asy.php



Coronal Mass Ejections (CME)

- Large eruption of plasma and magnetic field from the solar corona.
- More common during solar maximum.
- Most distinguishing feature: A strong magnetic field with large out-of-the-ecliptic components.
- Speeds from 250 to 3000 km/s (0.75-5 days to Earth).
- Slow CMEs merge into solar wind.
- Fast CMEs plow into solar wind and form shock waves.



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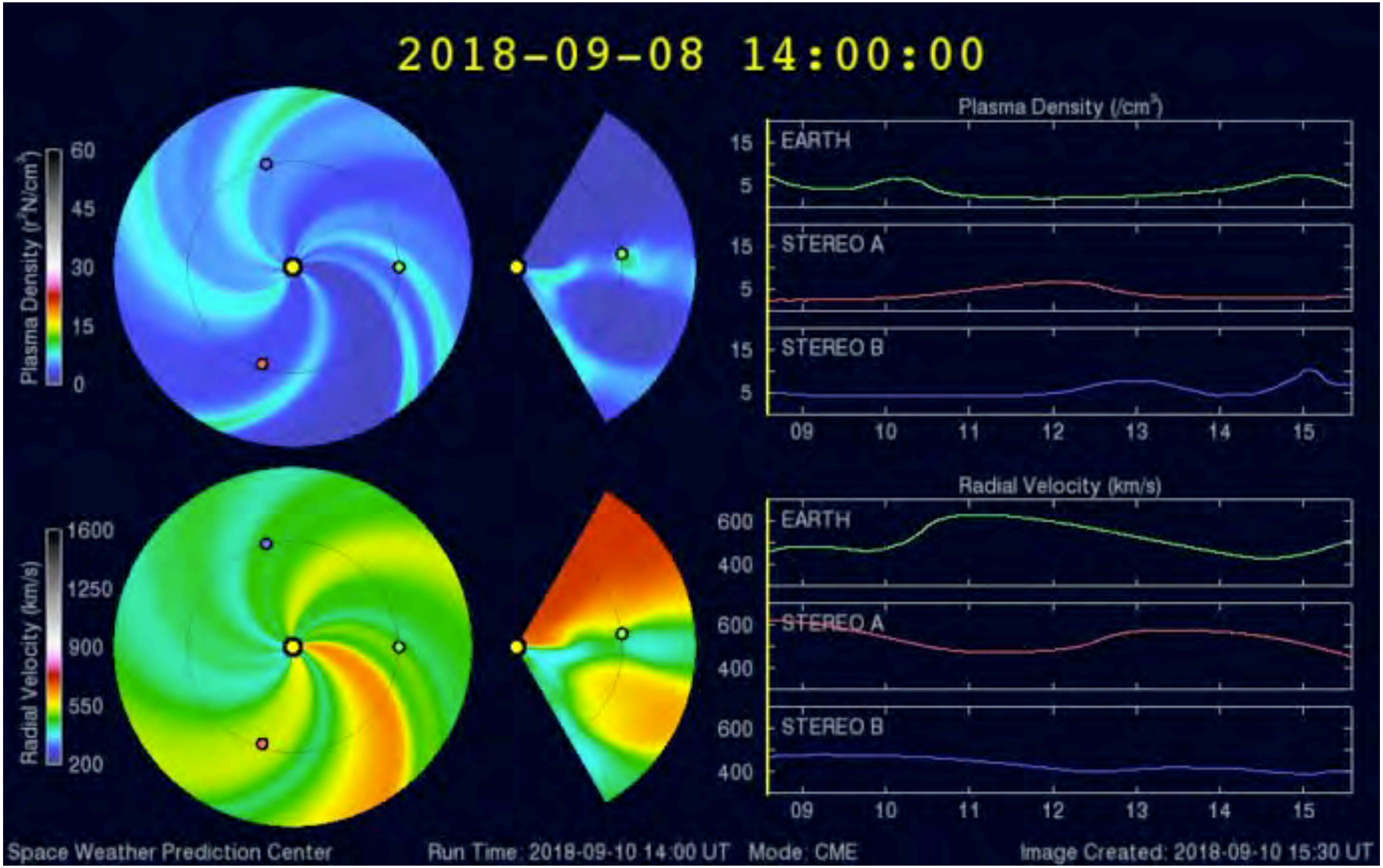
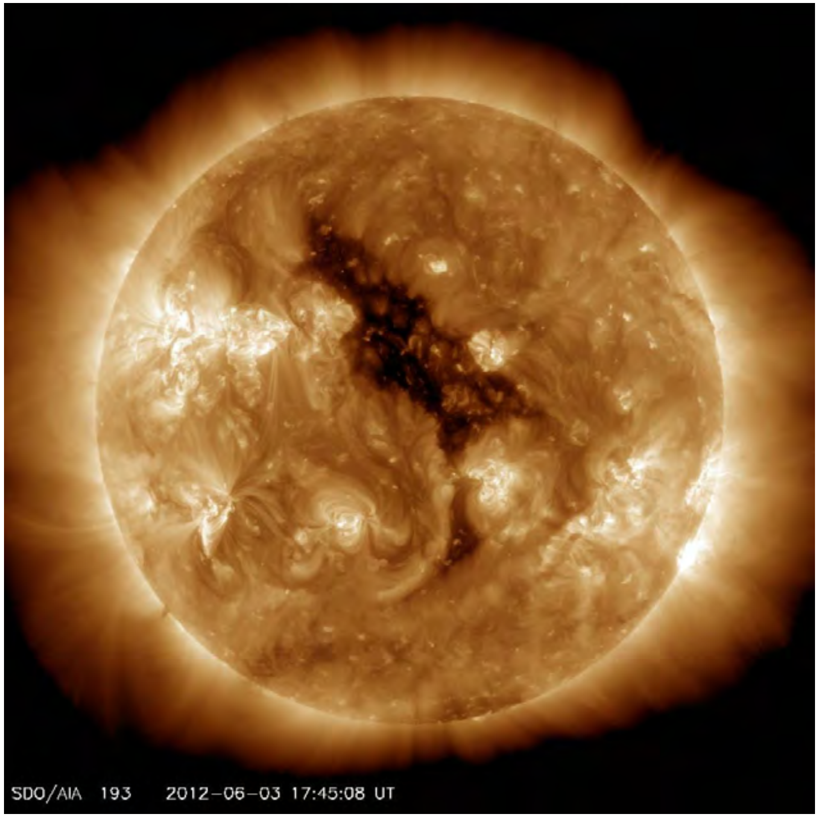
WSA-Enlil Model



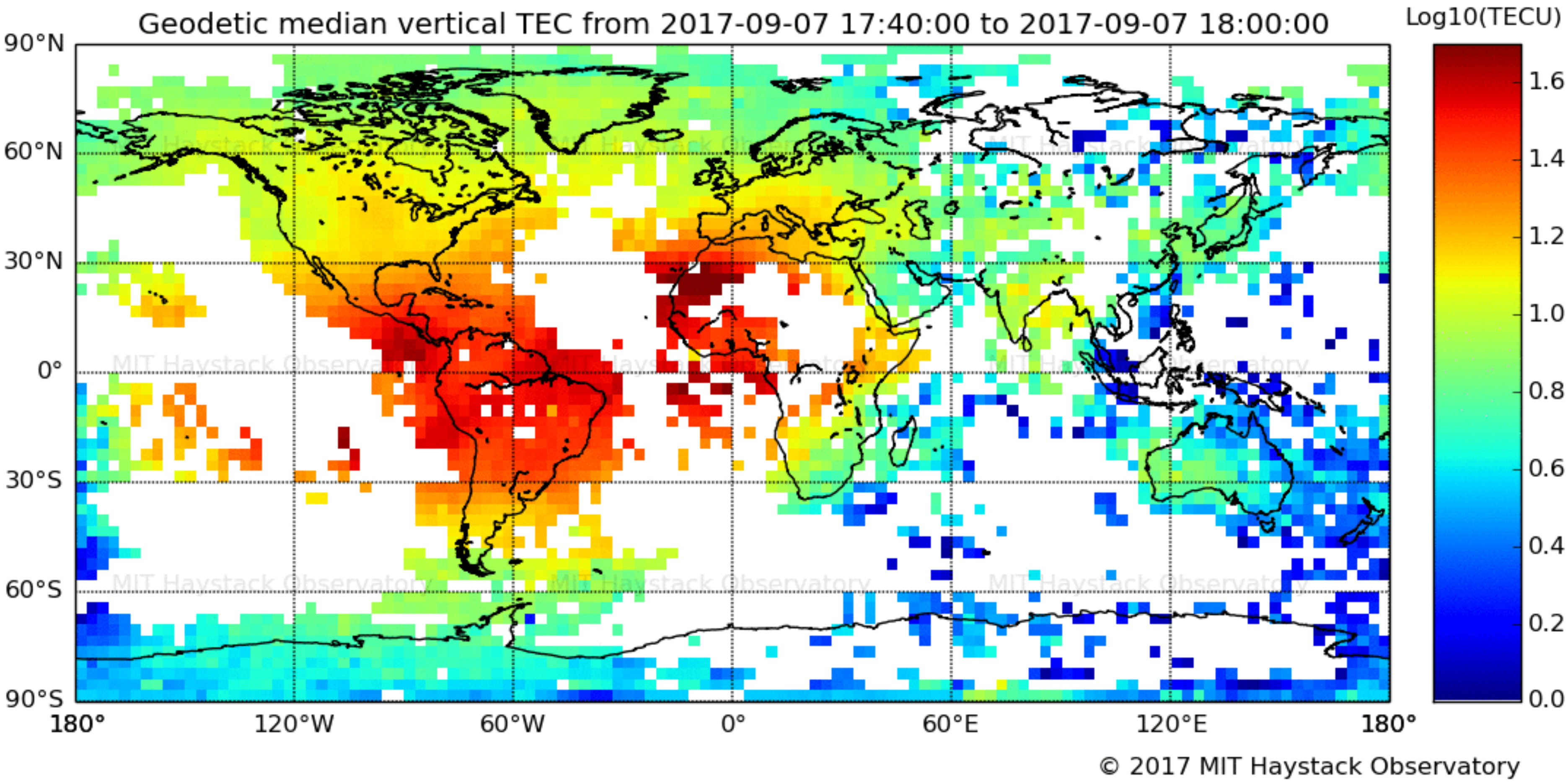
High Speed Streams (HSSs)

- High Speed Streams are fast moving solar wind released from coronal holes.
- HSSs overtaking slow plasma creates compressed Corotating Interaction Regions
- Coronal holes
  - Appear dark in EUV and soft X-ray because of cooler and less dense than surrounding plasma
  - Regions of open, unipolar magnetic fields (this allows HSS to escape)
  - More common during solar minimum
  - Can last through several solar rotations

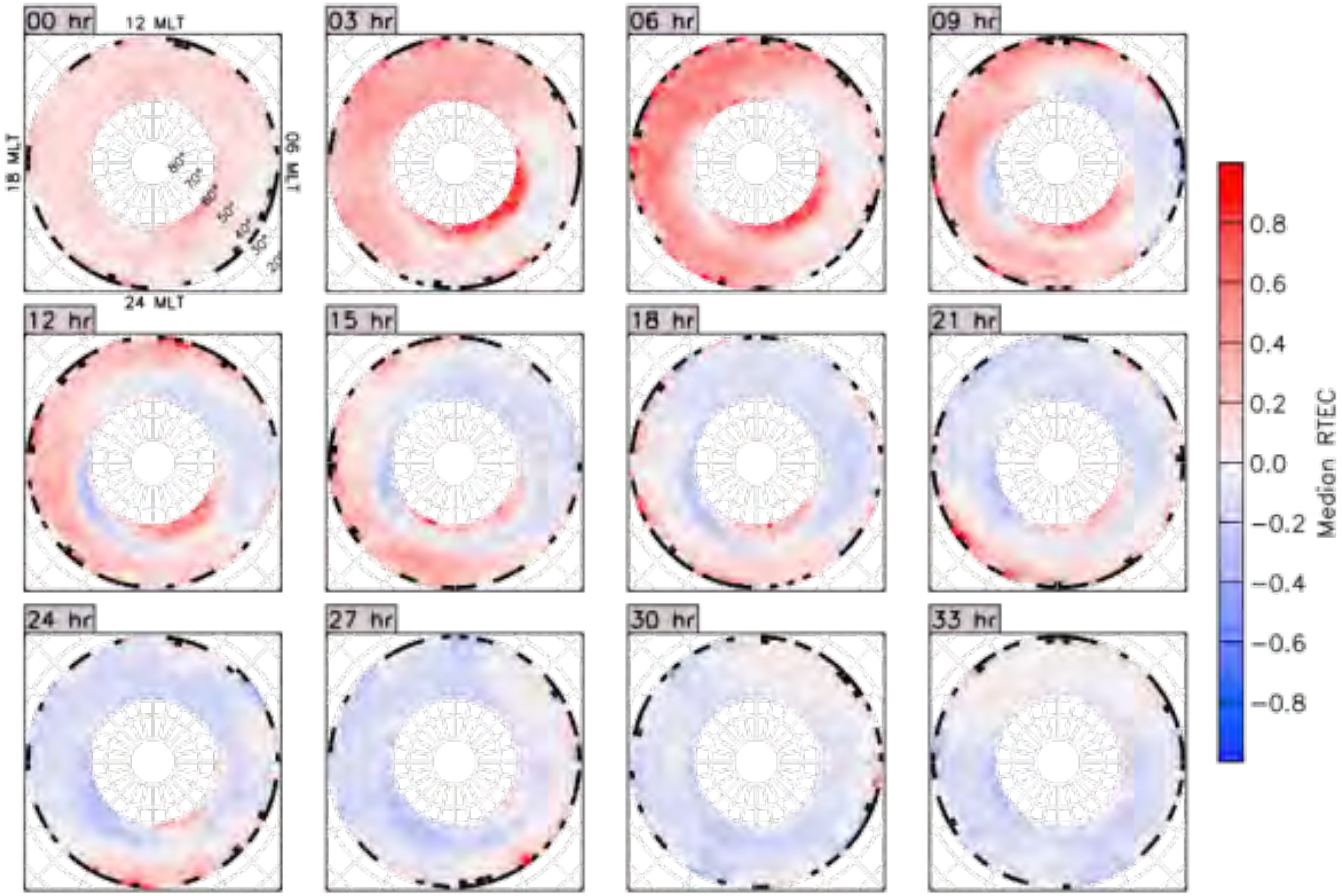


[NASA SDO]

Geomagnetic Storm



Ionospheric Storm Response

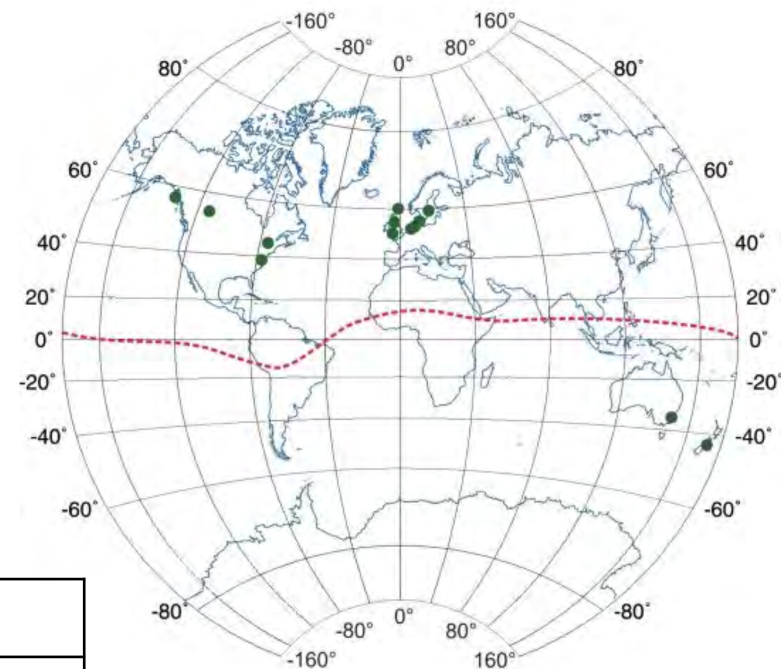


[Thomas et al., 2016]

Kp/ap

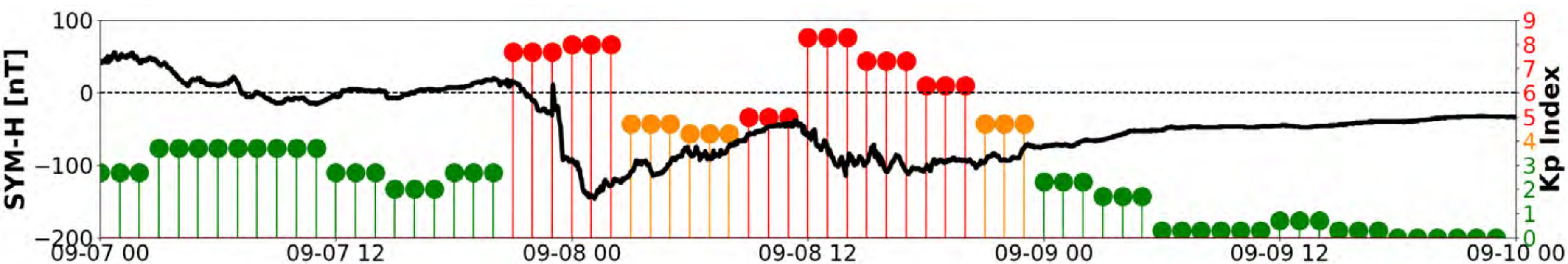
- Index of geomagnetic perturbation
- Kp is logarithmic, ap is linear
- 3 hour resolution
- "p" stands for planetary
- Perturbations are normalized for each station before being combined into a planetary value.

Kp/Ap Magnetometers



http://roma2.rm.ingv.it/

Kp	0	1	2	3	4	5	6	7	8	9
ap	0	4	7	15	27	48	80	132	207	400



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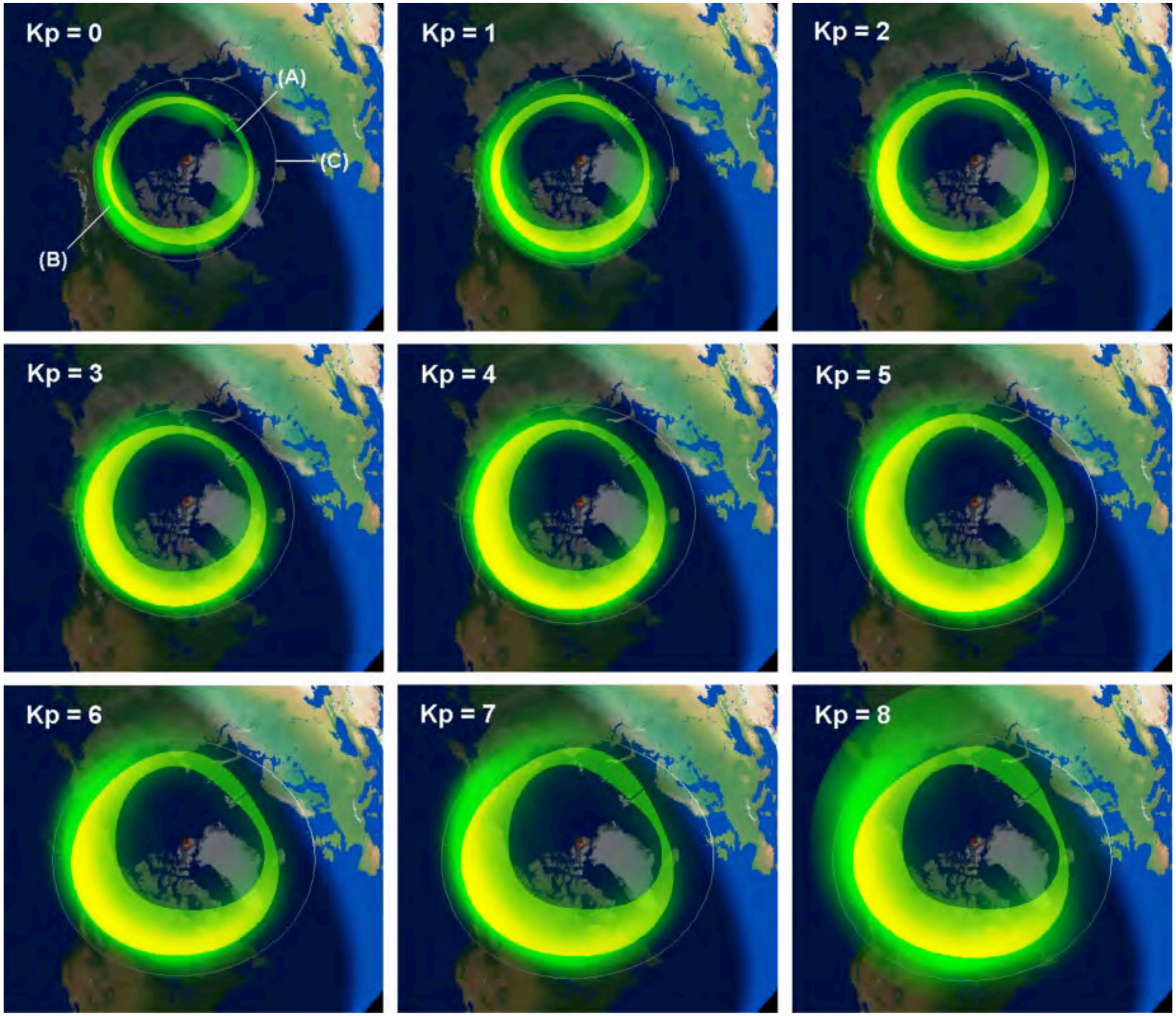
Kp and the Auroral Oval

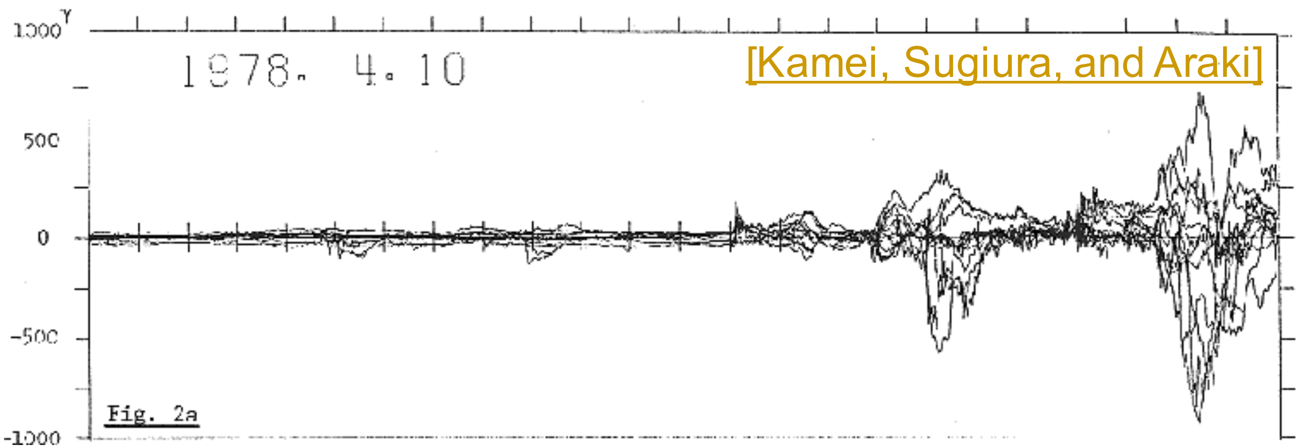


[Signeres et a:, 2011, doi:10.1051/swsc/2011003]

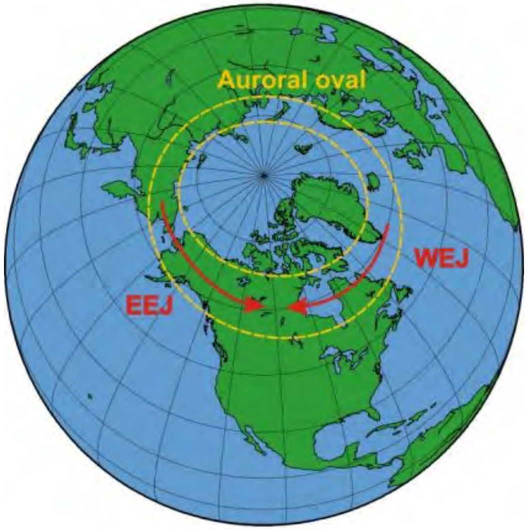
Auroral Electroject (AE/AL/AU)

Auroral Electrojet indices senses auroral zone currents with ground magnetometers

- Auroral Upper (AU): Eastward Electrojet
- Auroral Lower (AL): Westward Electrojet
    - Tracks substorm development
- AE = AU – AL: Integrated auroral activity

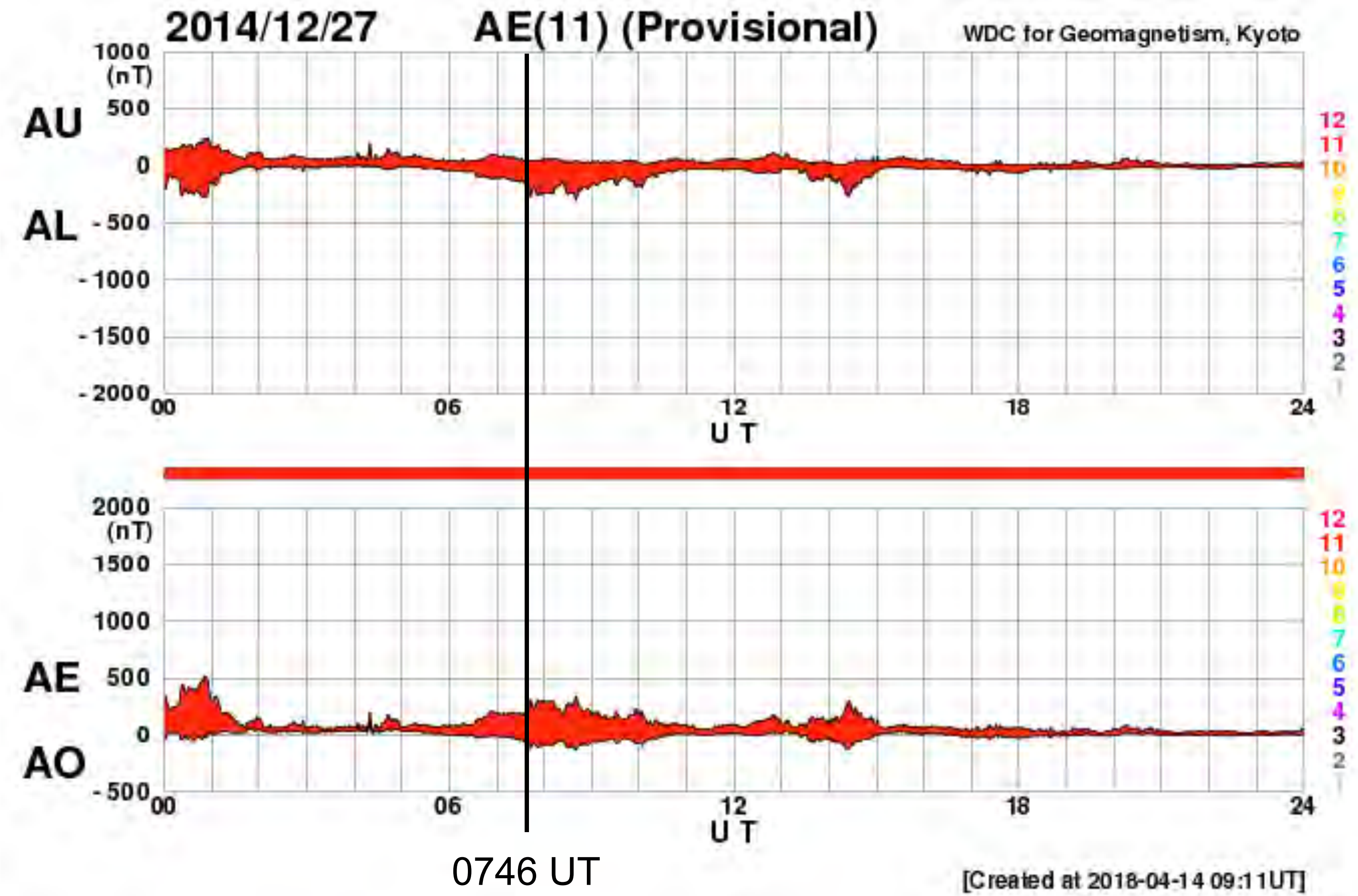


Day

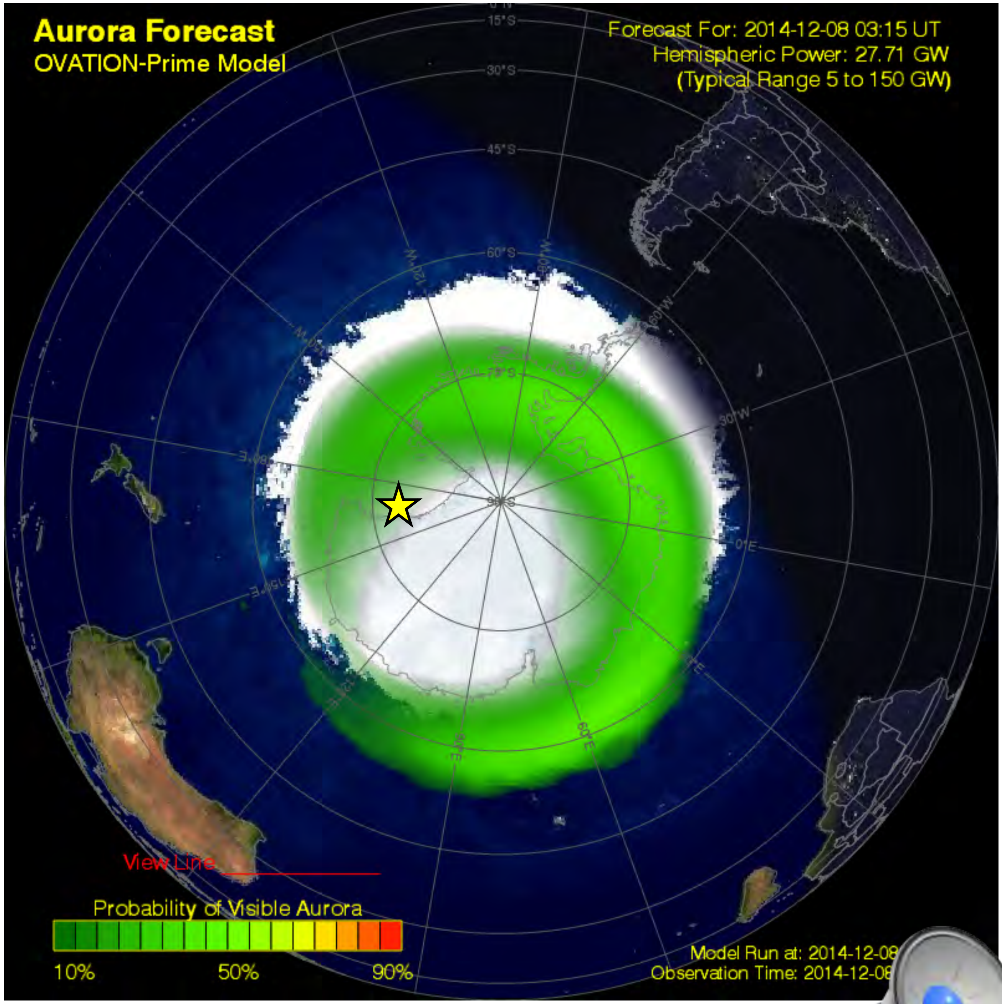


Night

Auroral Electroject (AE/AL/AU/AO)



Space Weather and Ham Radio

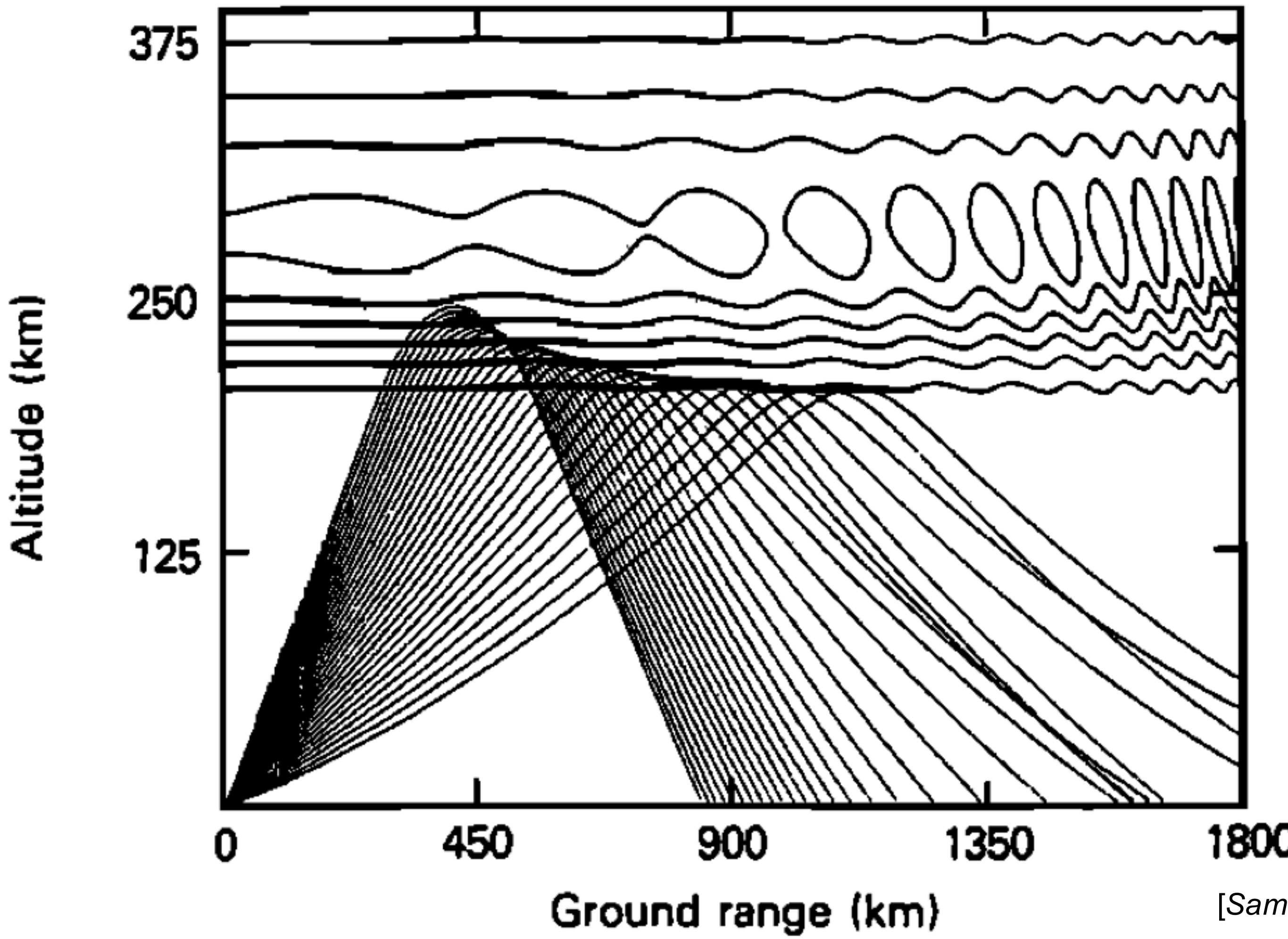


20141227 0746 UT Aurora @ KC4USV 14010 kHz

MSTID Science

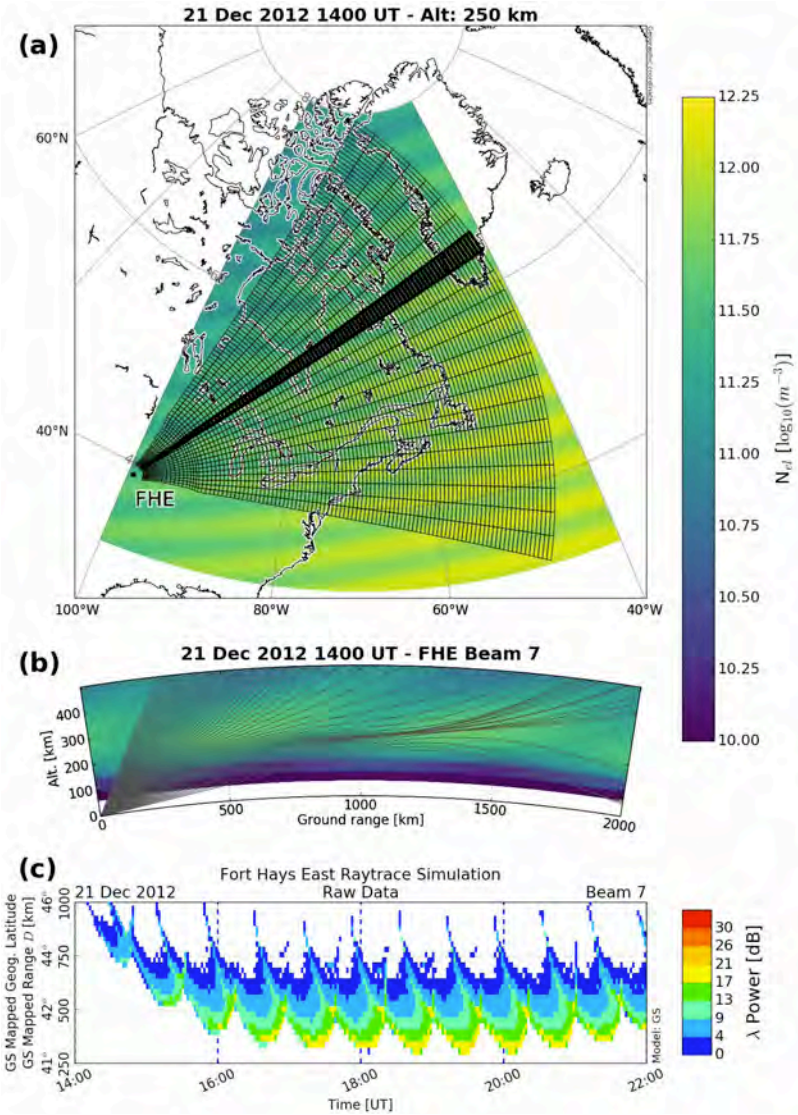
Medium Scale Traveling Ionospheric Disturbances

MSTIDs are a type of HF QSB



[*Samson et al.*, 1990]

Medium Scale Traveling Ionospheric Disturbances



Ray trace simulation illustrating how SuperDARN HF radars observe MSTIDs.

(a) Fort Hays East (FHE) radar field of view superimposed on a 250 km altitude cut of a perturbed IRI. FHE Beam 7 is outlined in bold.

(b) Vertical profile of 14.5 MHz ray trace along FHE Beam 7. Background colors represent perturbed IRI electron densities. The areas where rays reach the ground are potential sources of backscatter.

(c) Simulated FHE Beam 7 radar data, color coded by radar backscatter power strength. Periodic, slanted traces with negative slopes are the signatures of MSTIDs moving toward the radar.

[Frissell et al., 2016]

MSTIDs Caused by Aurora?

MSTIDs Caused by Aurora?

- Except for point sources, it is very difficult to track any single MSTID over its entire lifetime.
- Observational papers generally report
  - Equatorward propagation from high latitudes
  - Lots of activity in fall and winter
  - High and midlatitude MSTIDs are similar
- 1970s Theory Linked MSTIDs to Auroral AGWs
  - Lorenz Forcing by Auroral Current Surges
  - Joule Heating by Auroral Particle Precipitation

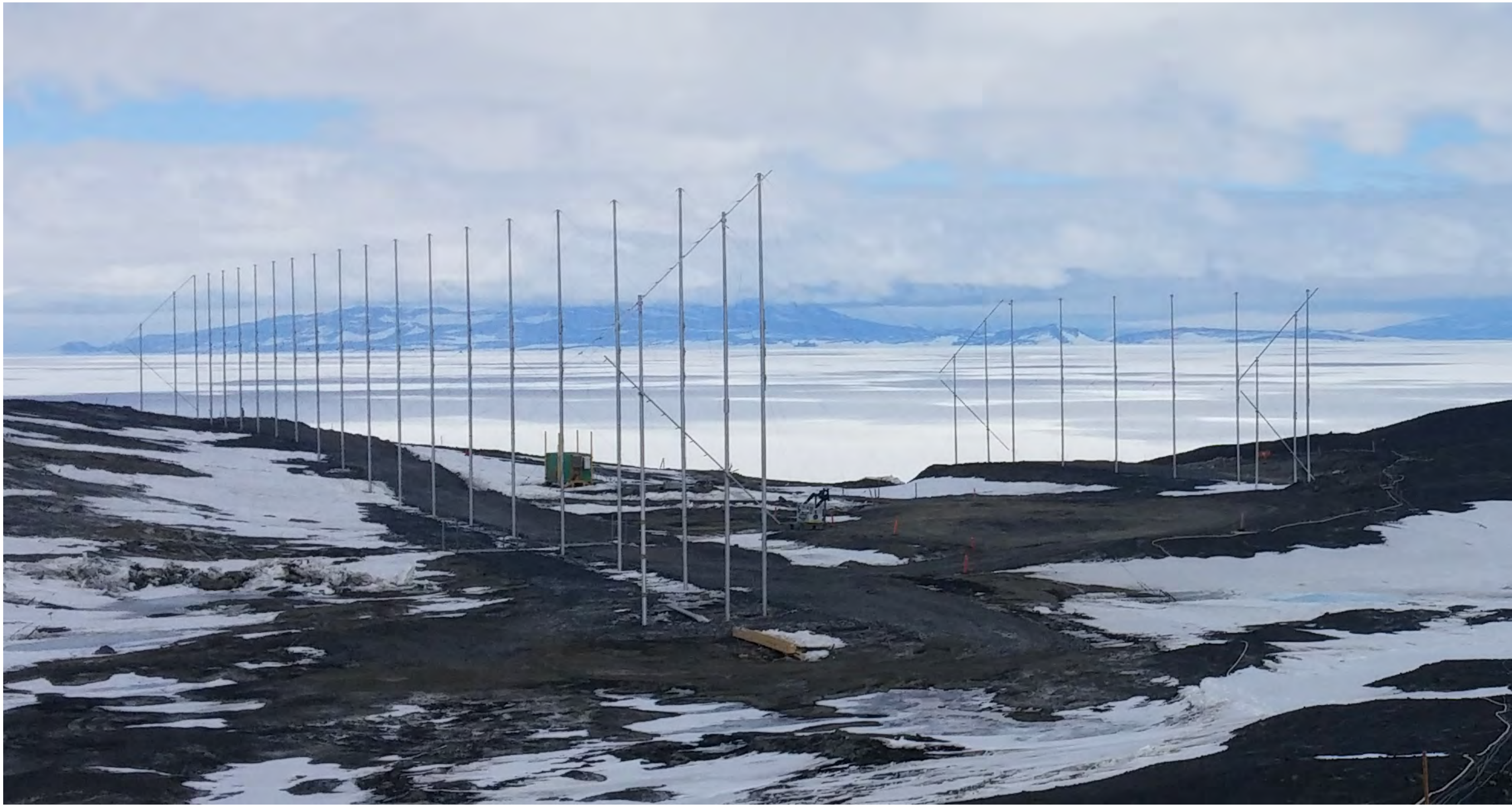
[e.g., *Chimonas and Hines, 1970*; *Francis, 1974*]

MSTIDs Caused by Aurora?

- Many observational papers try to link MSTIDs to geomagnetic activity.
  - Theory
  - Equatorward propagation
  - Originates from Auroral Zone
- Correlation of MSTID observations with space weather indices is marginal.
- If not the aurora, what else could it be?

[*Samson et al.*, 1989, 1990; *Bristow et al.*, 1994, 1996;
Grocott et al., 2013; *Frissell et al.*, 2014]

Super Dual Auroral Radar Network



SuperDARN Radar, McMurdo Station Antarctica

Photo N. Frissell, 2014

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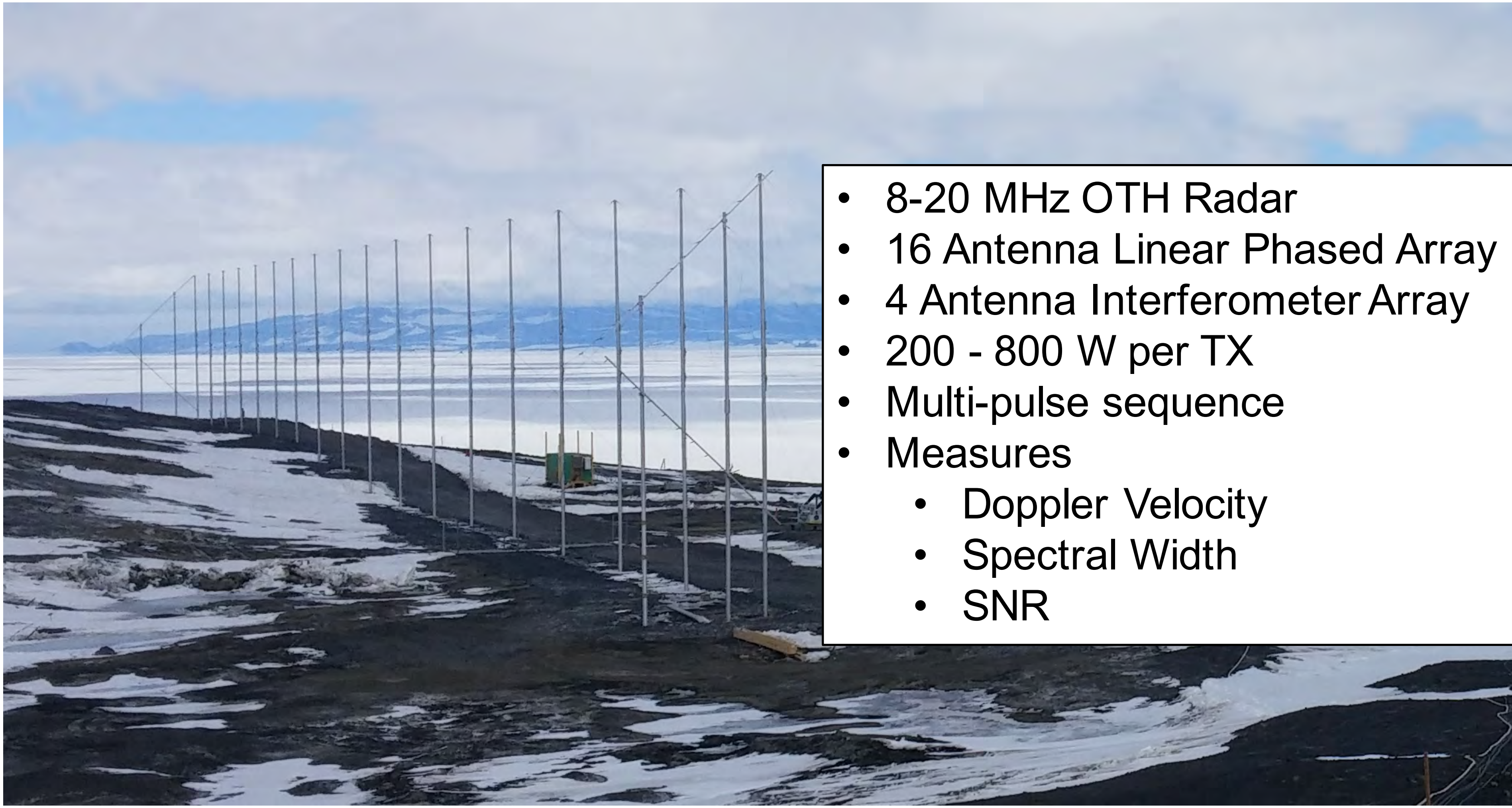
Super Dual Auroral Radar Network



- 8-20 MHz OTH Radar
- 16 Antenna Linear Phased Array
- 4 Antenna Interferometer Array
- 200 - 800 W per TX
- Multi-pulse sequence
- Measures
  - Doppler Velocity
  - Spectral Width
  - SNR

SuperDARN Radar, McMurdo Station Antarctica Photo N. Frissell, 2014

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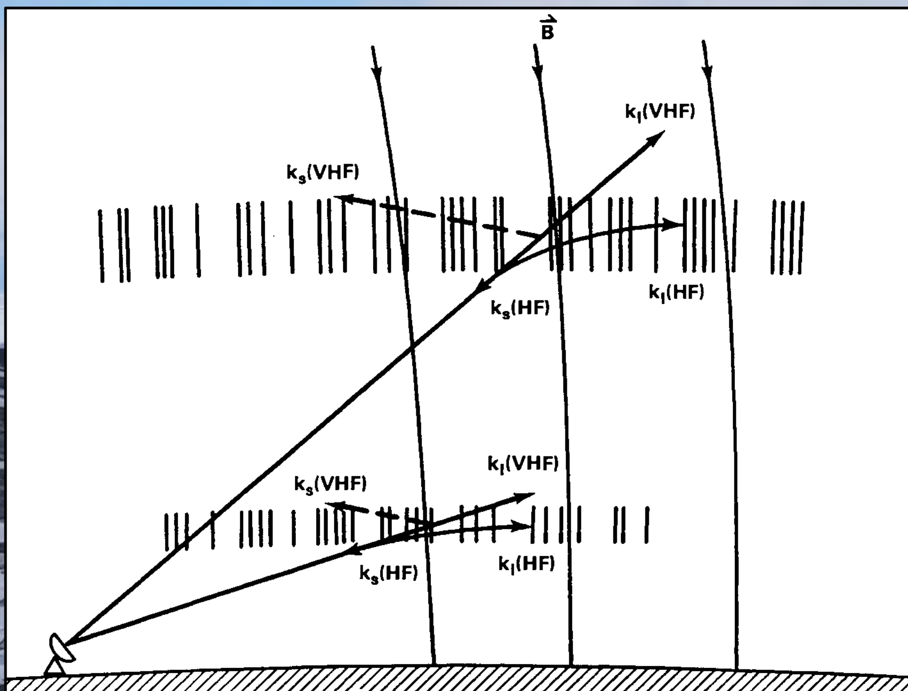
Super Dual Auroral Radar Network



[Greenwald et al., 1995]

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SuperDARN Radar, McMurdo Station Antarctica

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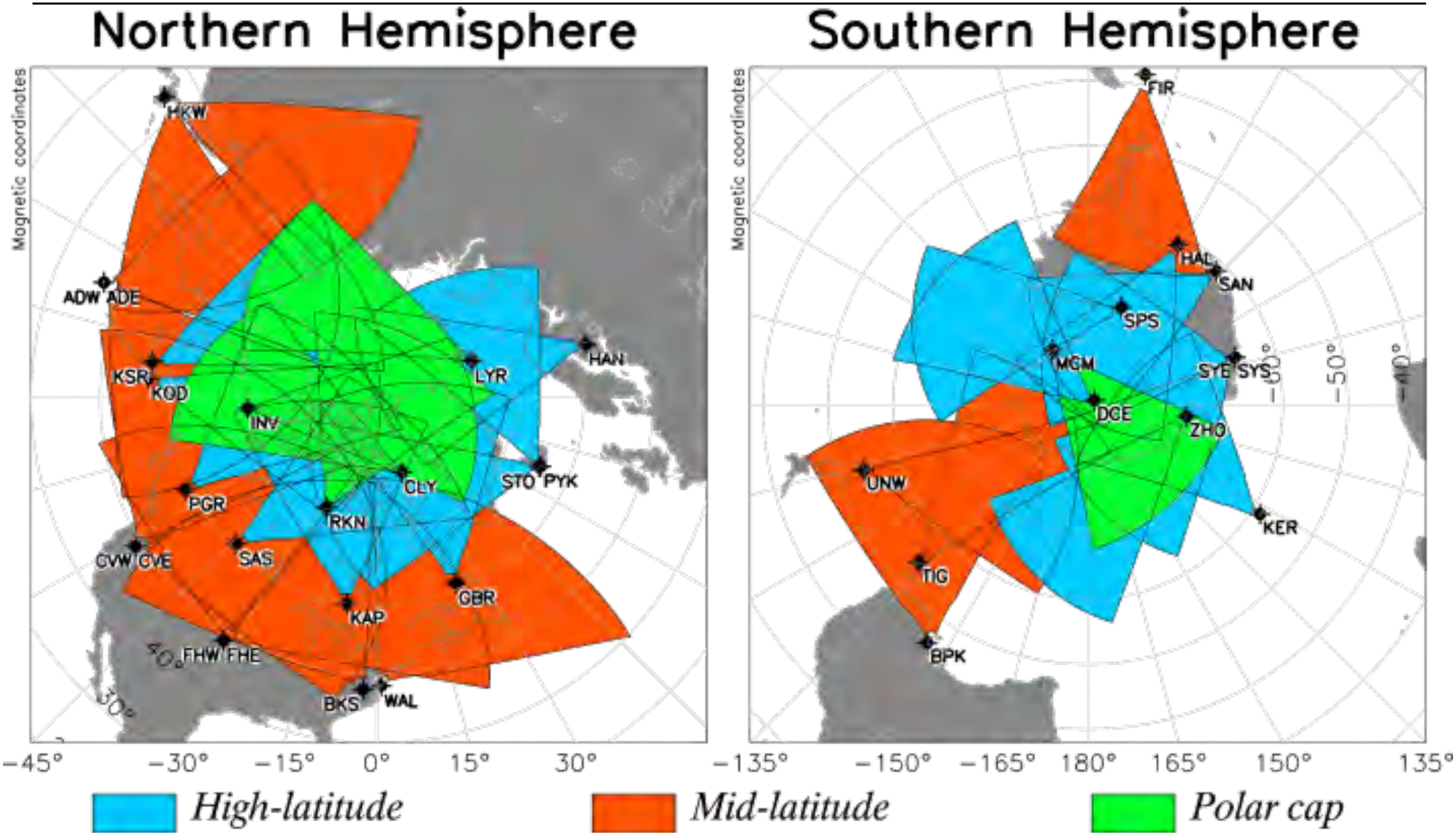
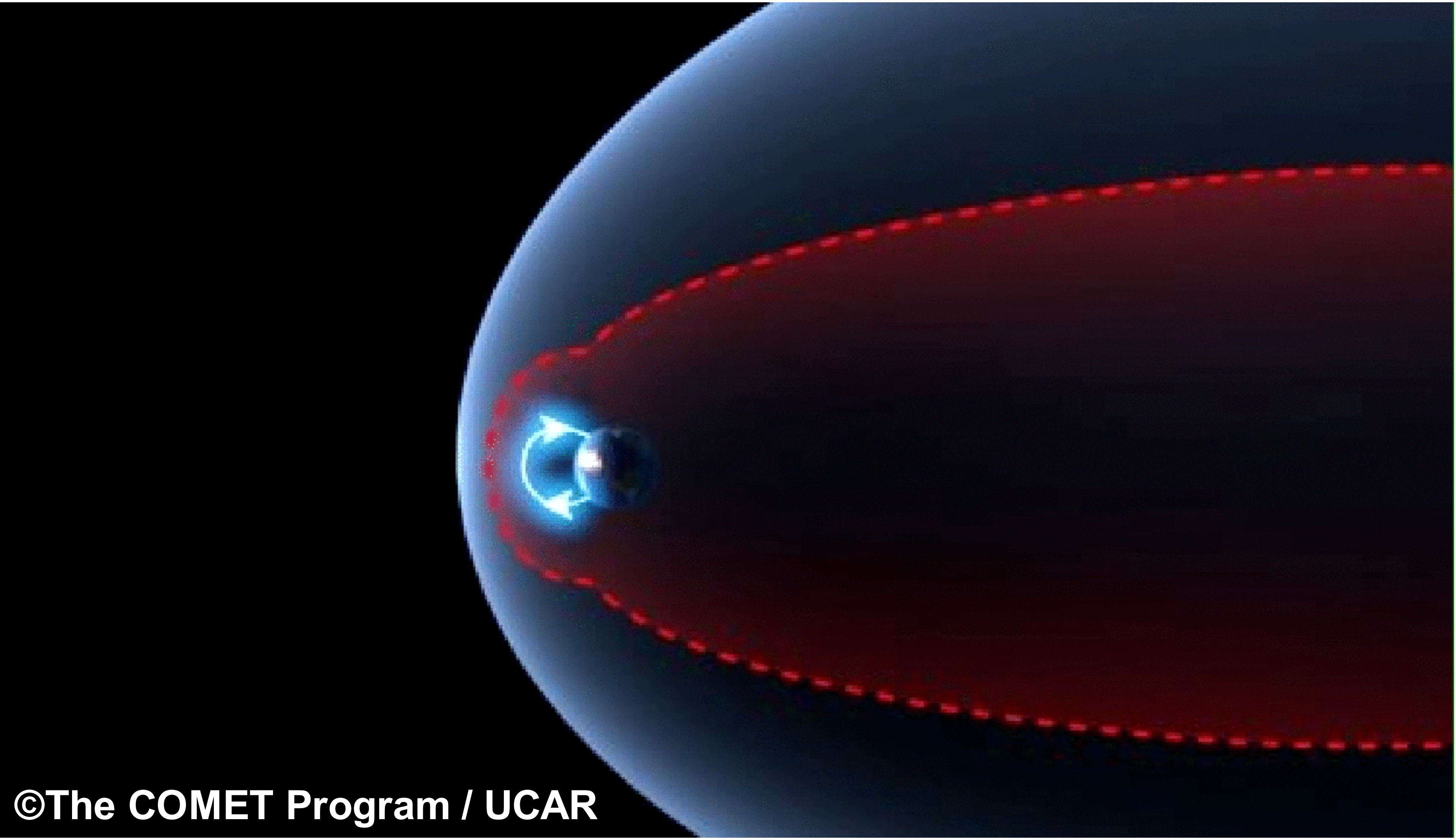
Super Dual Auroral Radar Network



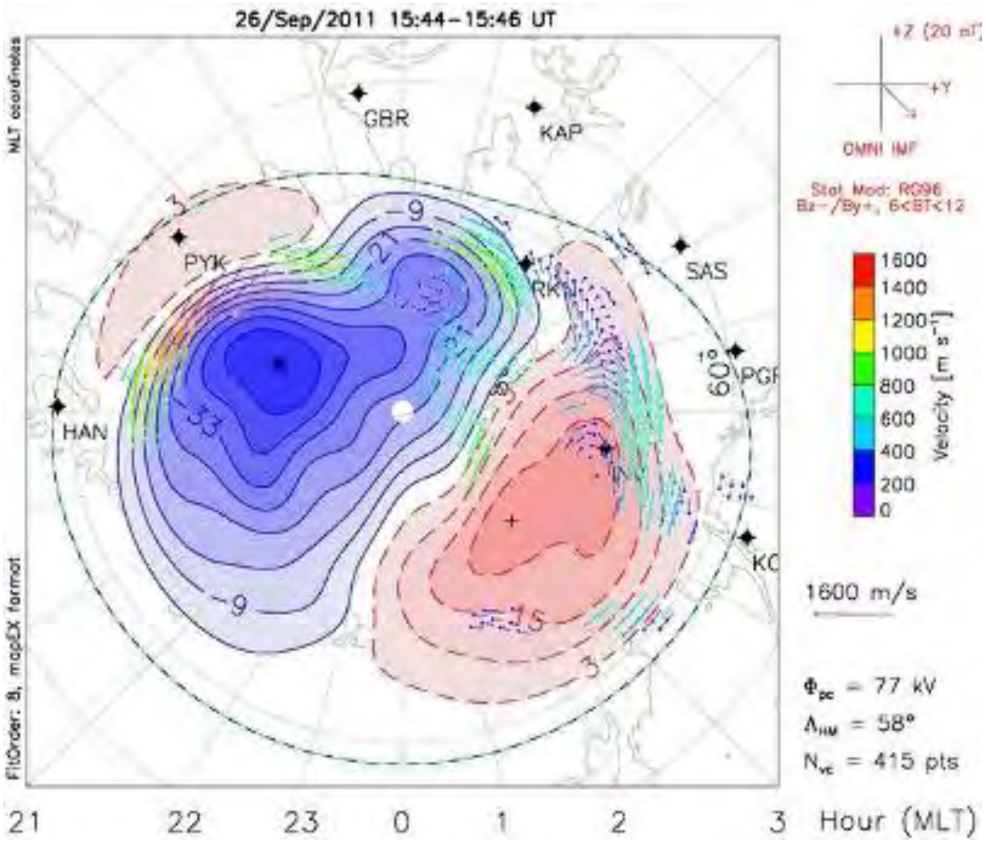
[http://vt.superdarn.org, 15 Sept 2018]

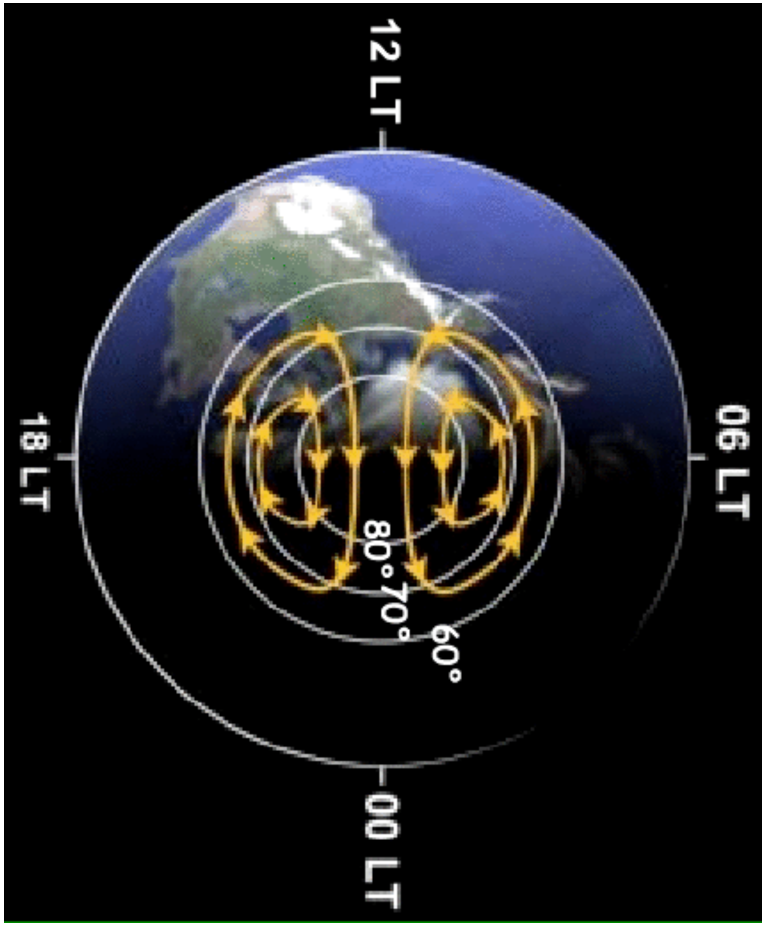
Magnetospheric Convection



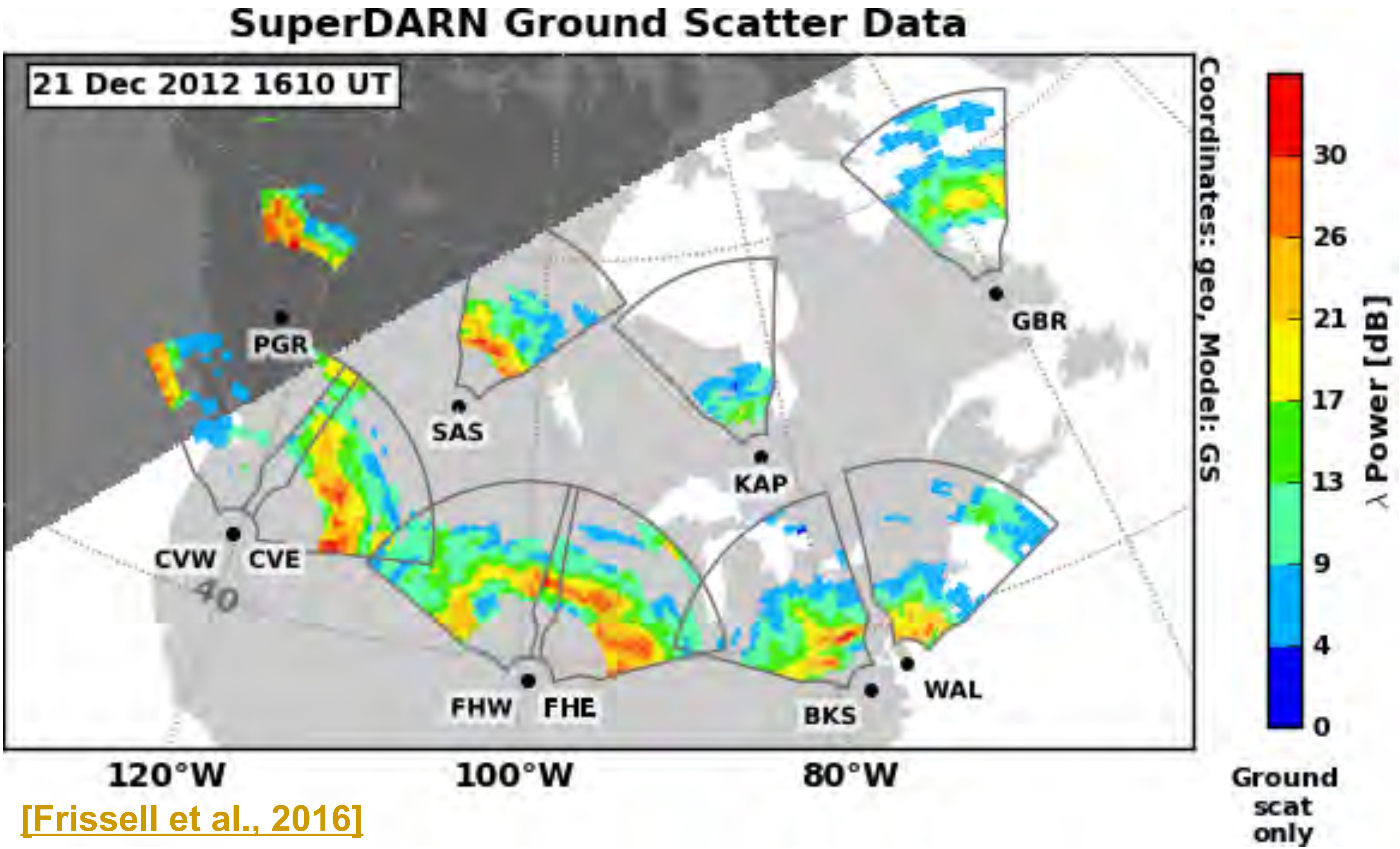
Super Dual Auroral Radar Network

SuperDARN
Global Ionospheric Convection Maps





SuperDARN MSTID Study



[Frissell et al., 2016]

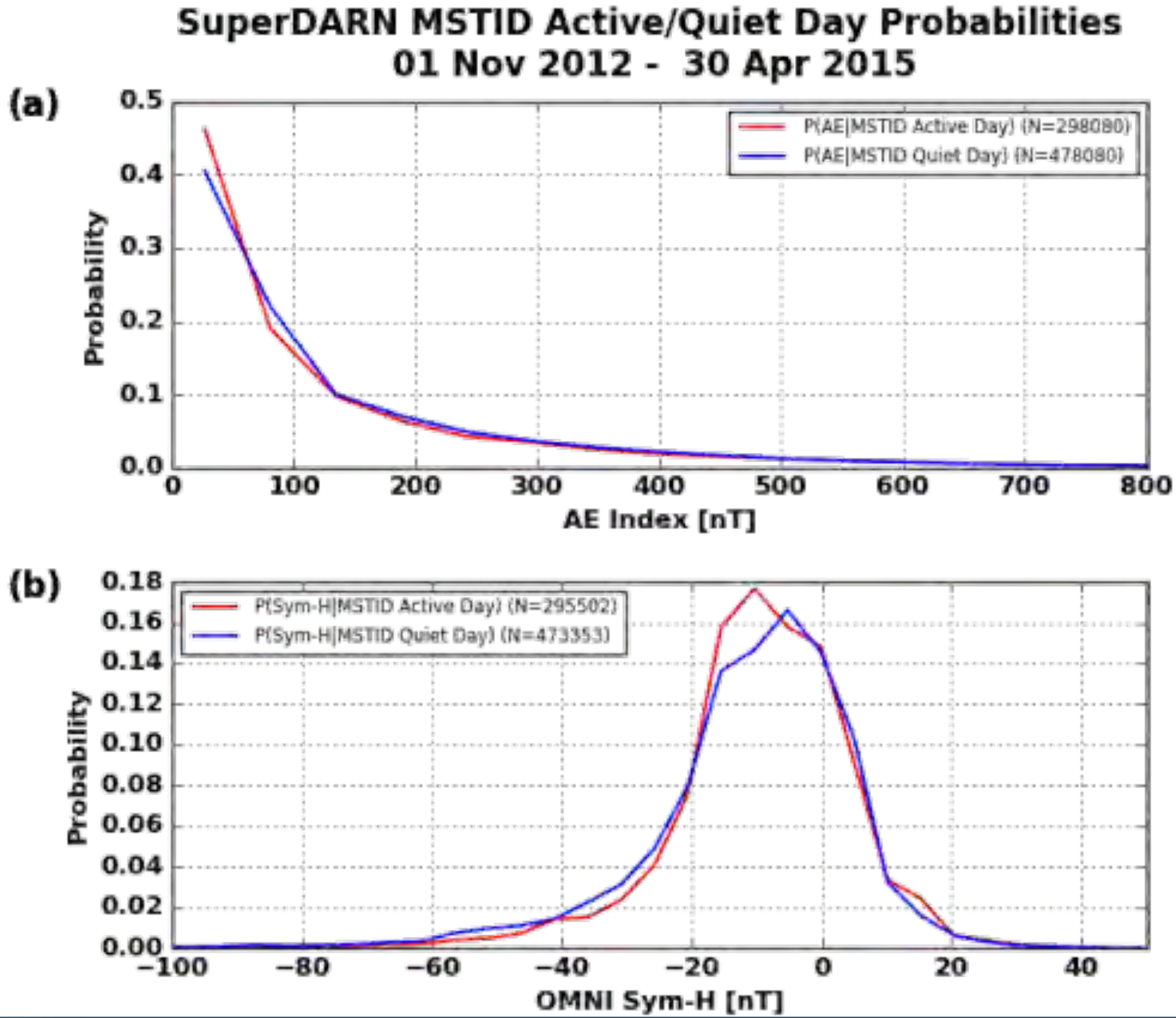
Is it the Aurora?

MSTID Active

MSTID Quiet

AE

SYM-H



It's Cold Outside!

The Guardian

Video: Cold and dangerous blast of polar air grips much of United States

US polar vortex: extreme cold weather heads to east coast - live

- **Four die in central US temperatures as low as -37F (-38.3C)**
- **Cold air moves towards east coast**
- **Live coverage of all developments**
-

Paul Owen

Tue 7 Jan 2014 11.47 EST

4.47pm

Summary

Here is a summary of the key events of the day so far:

- **Cold air from the Arctic meant record cold temperatures spread from the Midwest to the south and east of the US and eastern Canada on Tuesday, affecting as many as 187 million people.**
- **It was hazardous to go outside in many places, thousands of flights were cancelled, and schools and businesses were shut in some locations.**
- **Temperatures were expected to be 25 to 35F (14-19C) below normal from the Midwest to the Southeast, the National Weather Service warned.** In New York's Central Park, the temperature was 4F (-16C), with 32mph winds making it feel much colder. Homeless shelters were "overflowing", Reuters reported. Chicago was -9F (-23C), Detroit -11F (-24C), Washington 9F (-13C) and Boston 12F (-11C). Even in the south, Atlanta recorded its coldest weather for the date for 44 years, with the temperature dropping to 6F (-14C).
- **Wholesale electricity prices spiked and the price of oil rose 42c to nearly $94 a barrel.**
- **Many across the US and Canada took to Twitter and Instagram to post pictures and details of their freezing homes and chilly commutes to work.**

4.25pm

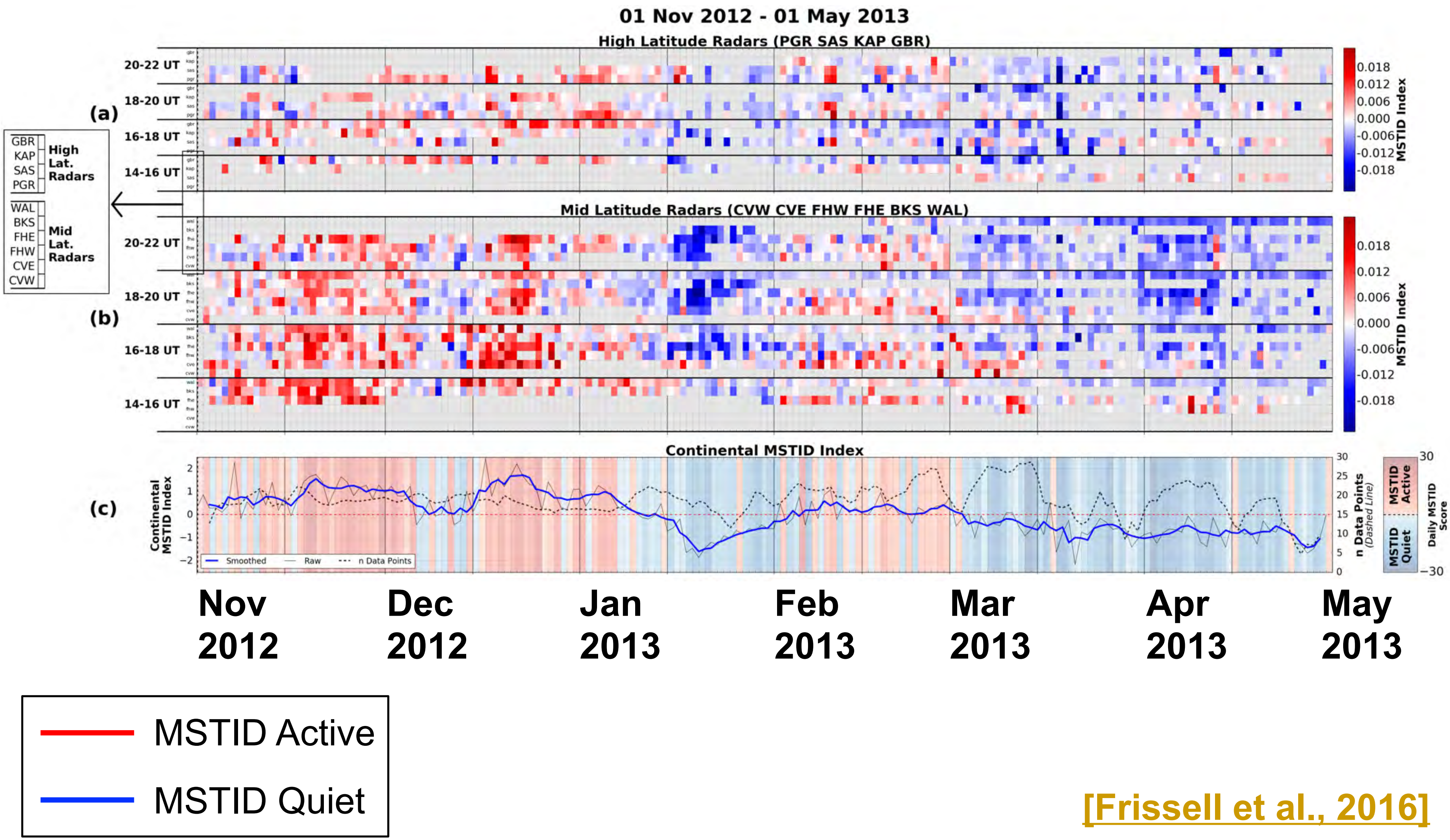
I've just been speaking to Margot Douaihy in **Northampton, Massachusetts**, a "beautiful college town of about 30,000 people" three hours north of Manhattan.

We're used to inclement weather in New England, of course, but the sudden deep chill and strong winds make being outside unbearable. The air is impossible. Walking outside for five minutes was painful: a deep breath is like inhaling fire, my knees locked, my fingers went numb in my gloves. Any snow that remained from the weekend blizzard turned into cement.

Our New York Times froze to the sidewalk; I can't move it. It adorns the front sidewalk like a stone statue. The thin ice is mottled, thicker ice sheets are clear. The only colour this morning was the frozen canoe in the backyard. People inch by, covered head to toe, like astronauts.

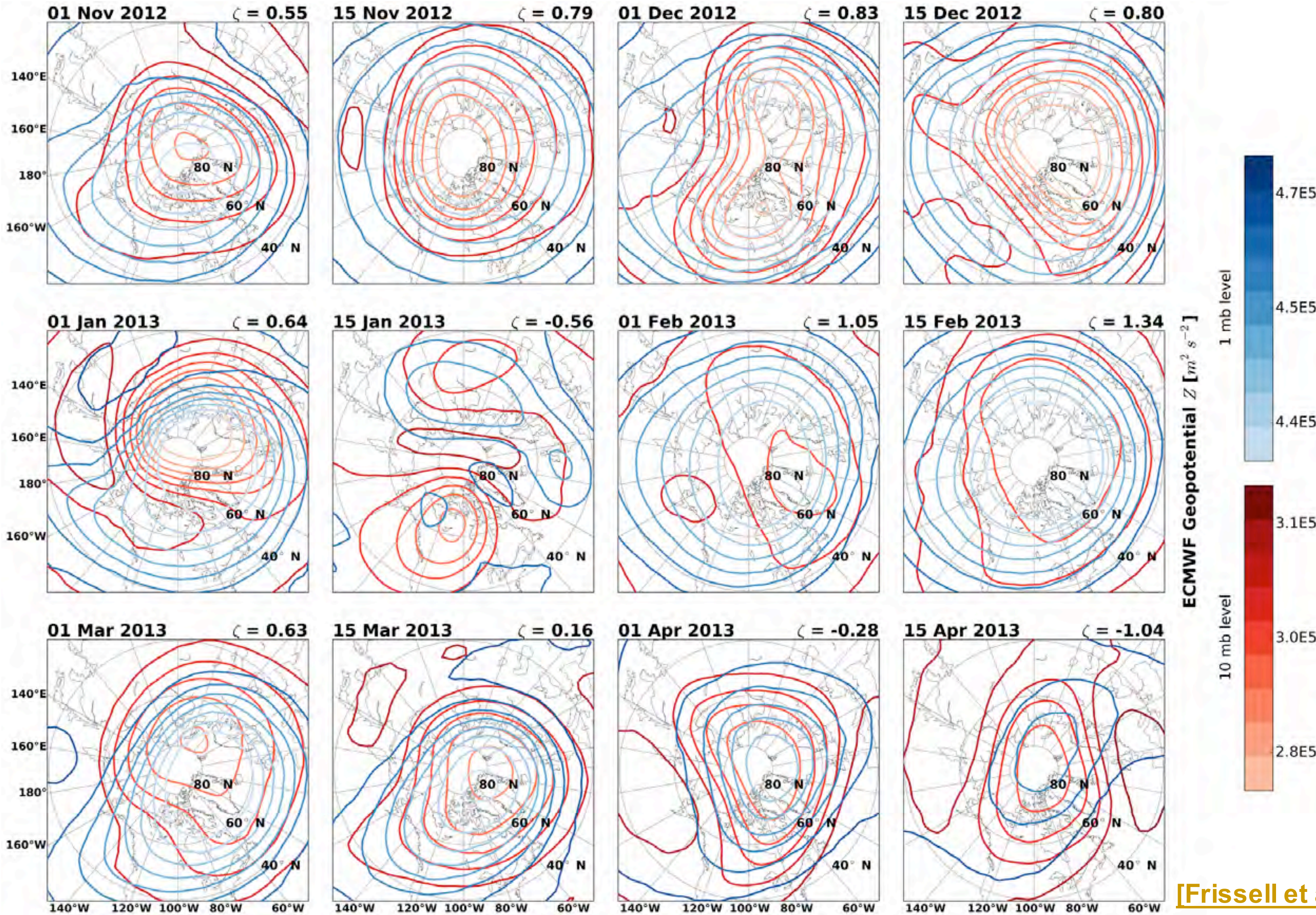
NJIT Center for Solar-Terrestrial Research

MSTIDs Nov 2012 – May 2013



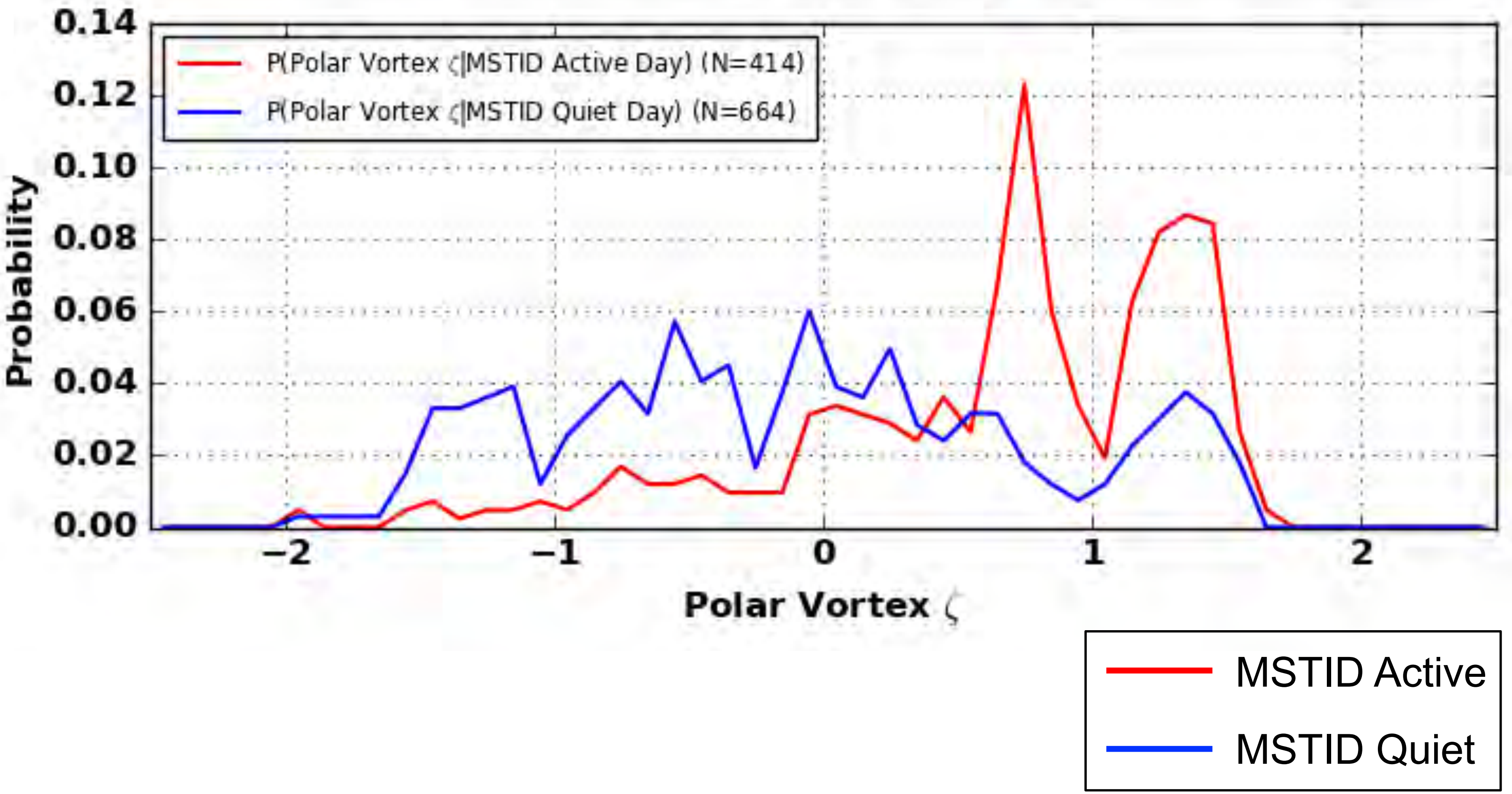
[Frissell et al., 2016]

Polar Vortex



[Frissell et al., 2016]

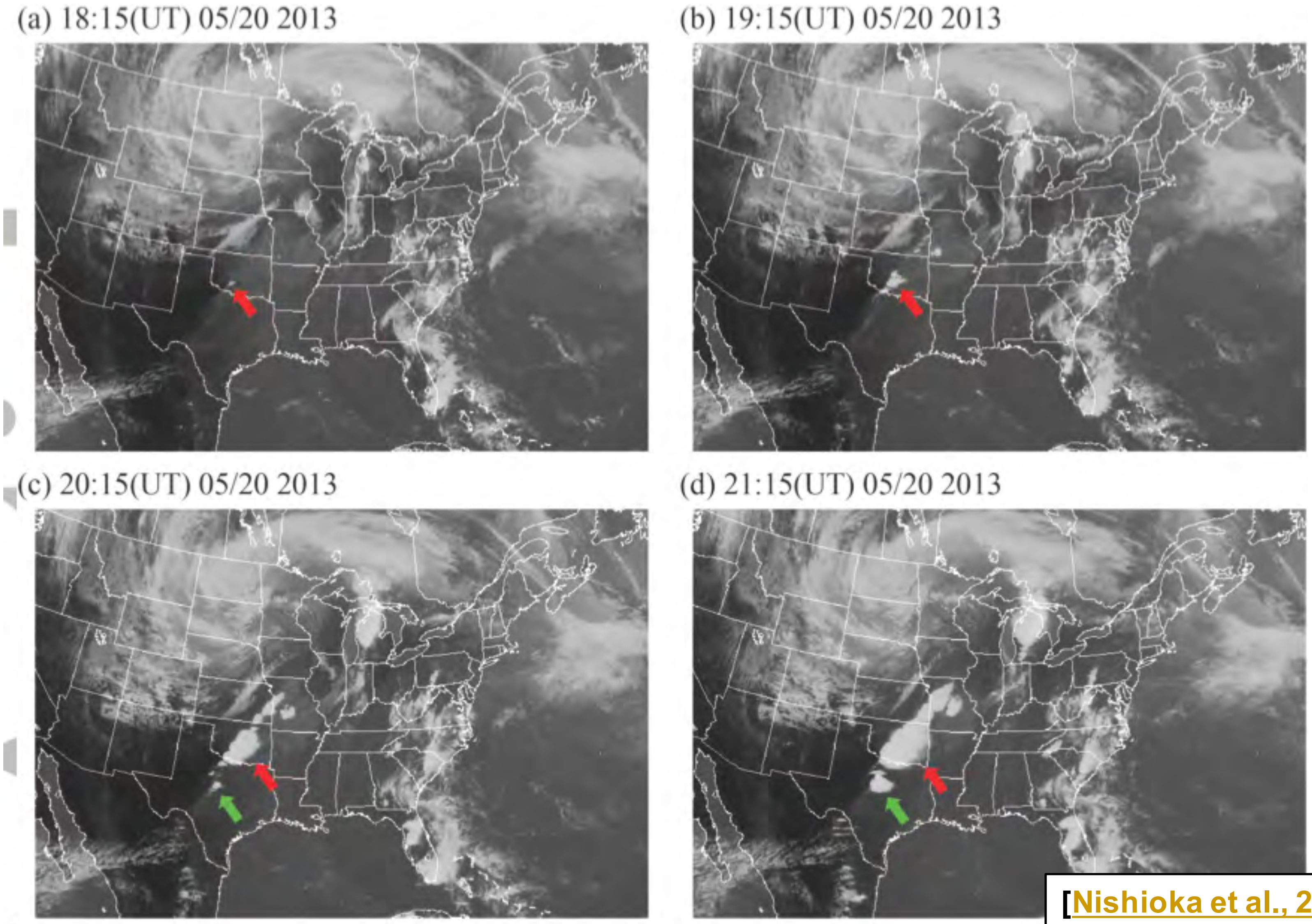
Correlation with Polar Vortex!



Making a Discovery

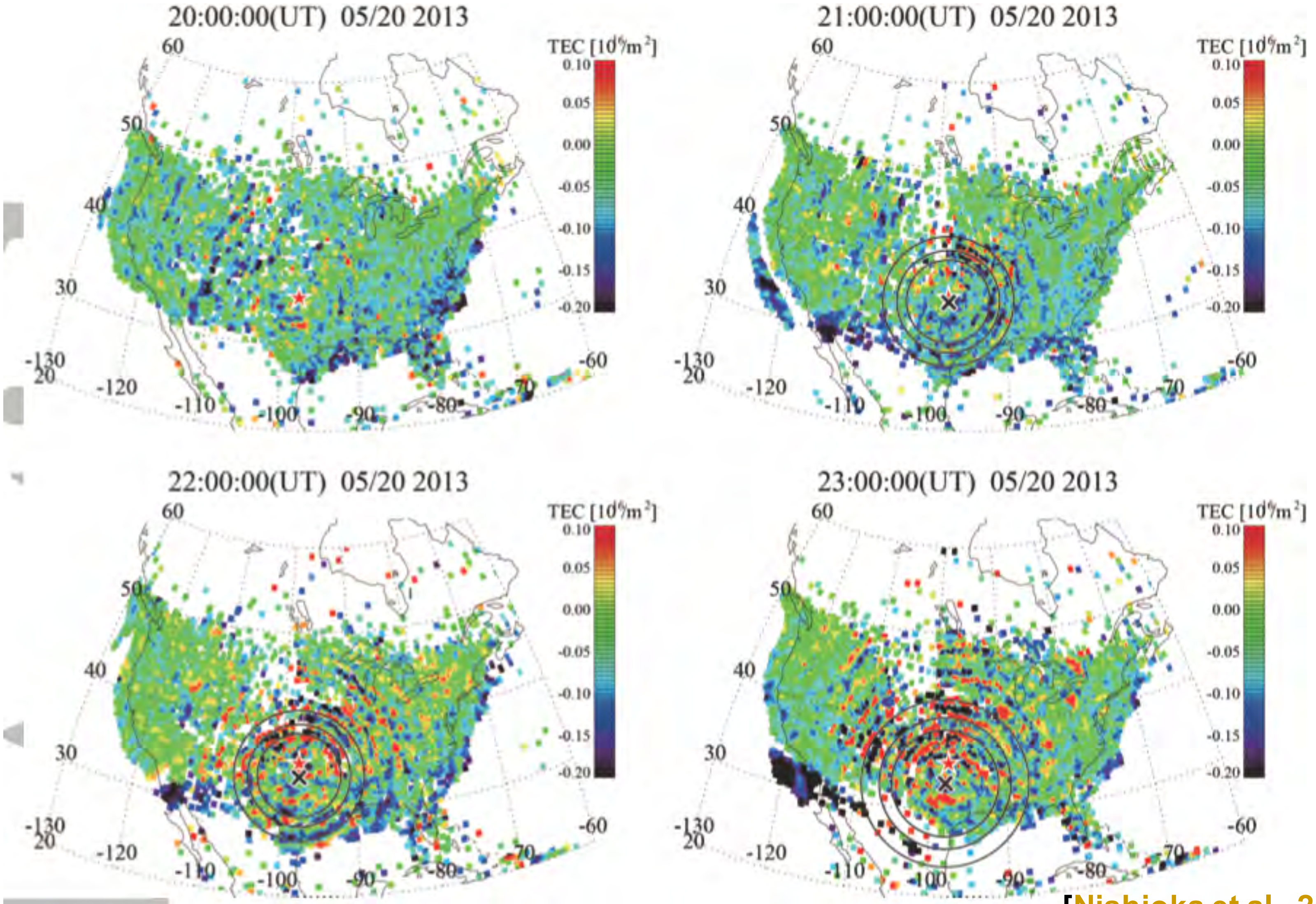
- MSTID SuperDARN Science worked just by measuring amplitudes AND putting them into a coherent picture.
- SuperDARN SNR is NOT calibrated across radars
- Needed a way to normalize everything.
- We could still get good science out of that.
- By putting together a coherent picture from many sensors, we made a discovery!
- We could do the same with Ham Radio.

Development of Tornado Cell



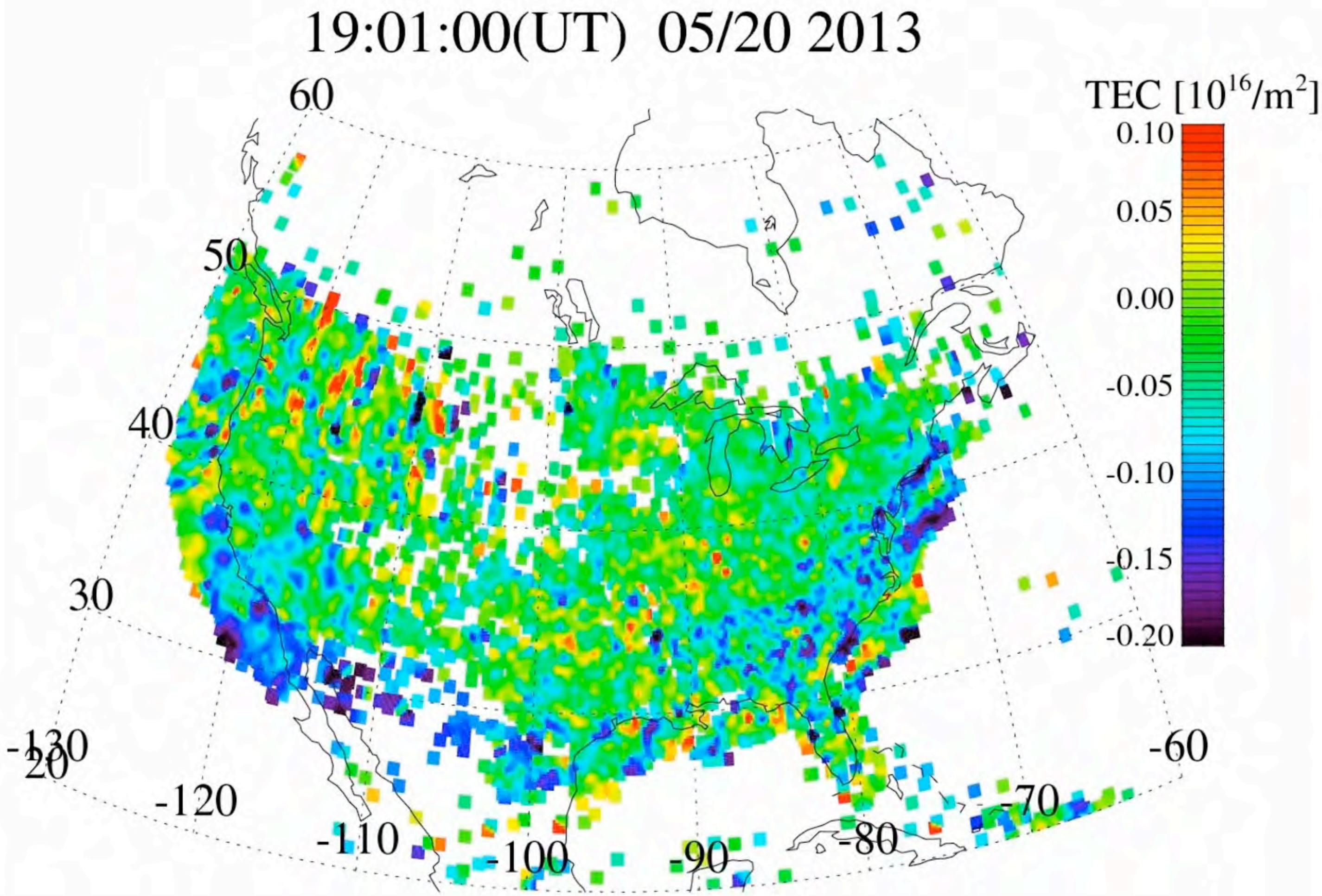
[Nishioka et al., 2013]

MSTID Resulting from Tornado



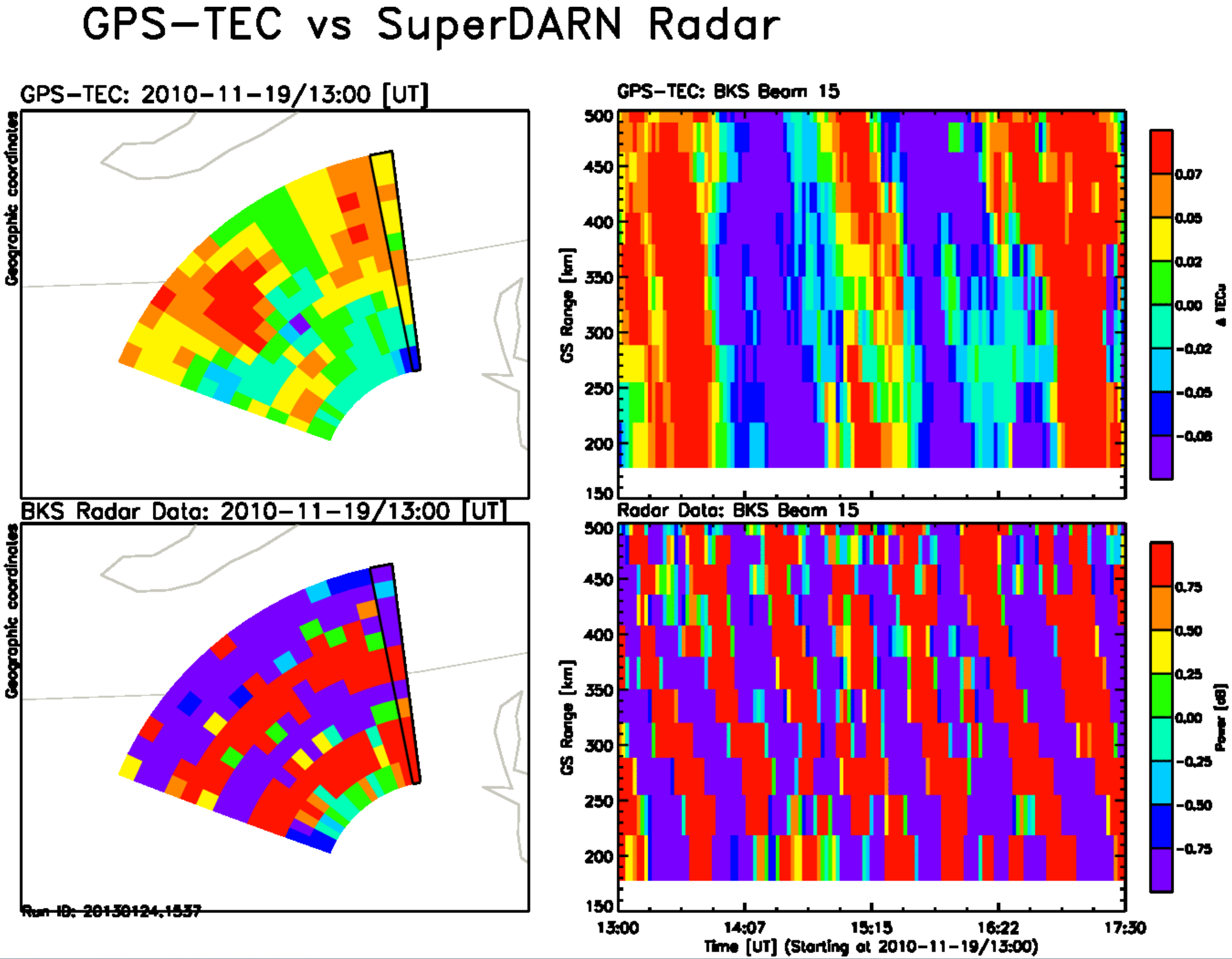
[Nishioka et al., 2013]

MSTID Resulting from Tornado



[Nishioka et al., 2013]

GPS-TEC vs SuperDARN TIDs



My Vision of a Personal Space Weather Station

Personal Terrestrial WX Station

- Multi-instrument
- Internet Connected
- Easy Set-Up
- Reasonable Cost

Ambient Weather WS-2902

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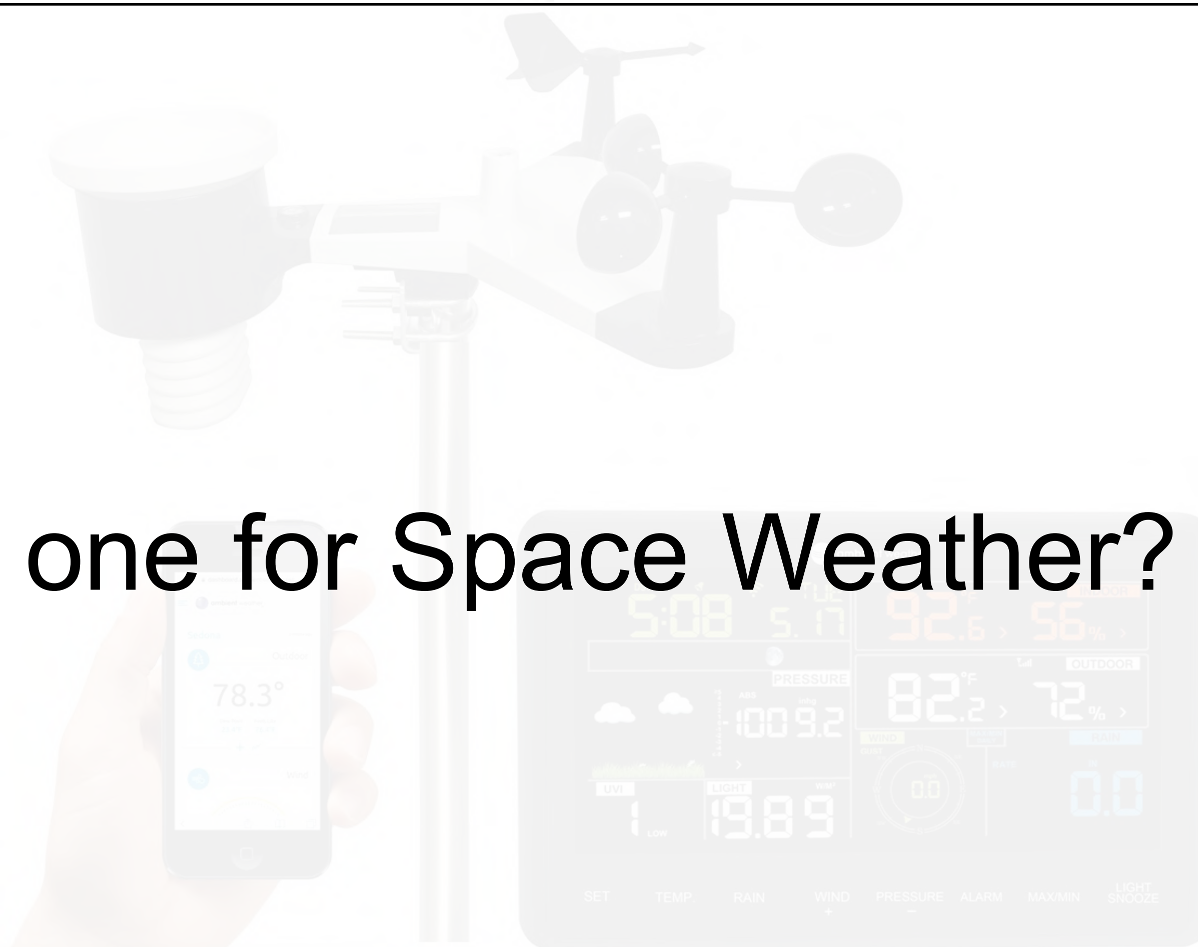
Personal Terrestrial WX Station

- Multi-instrument
- Internet Connected
- Easy Set-Up
- Reasonable Cost



Ambient Weather WS-2902

Can we build one for Space Weather?

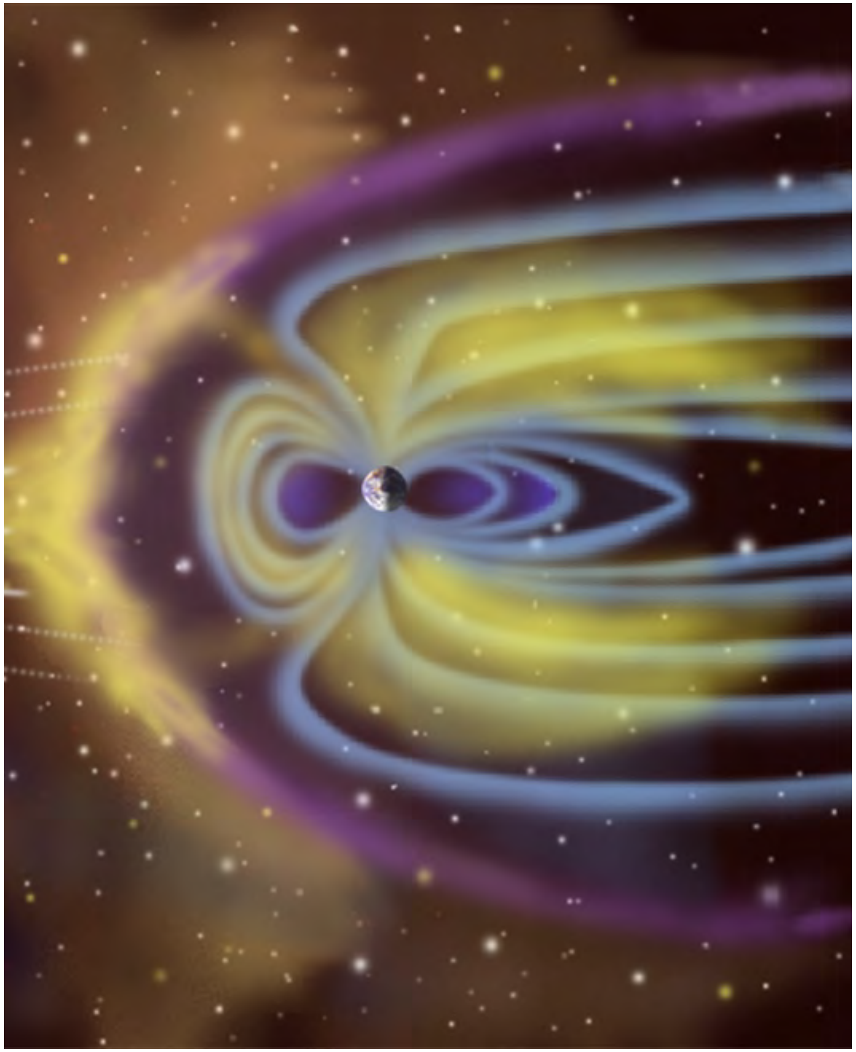
Instrument Possibilities

- Ground Magnetometer?
- GPS-TEC Receiver?
- Ionosonde?
- Riometer?
- WWV/Standards Station Monitor?
- RBN/PSKReporter/WSPR Receiver?
- Lightning Detector?
- Others?

What makes sense for a personal, ground-based local station?

Ground Magnetometers

- Detect Ionospheric & Space Currents
- Geomagnetic Storms
- Geomagnetic Substorms
- Kp and Ap are derived from GMAGs data.



GPS Total Electron Content

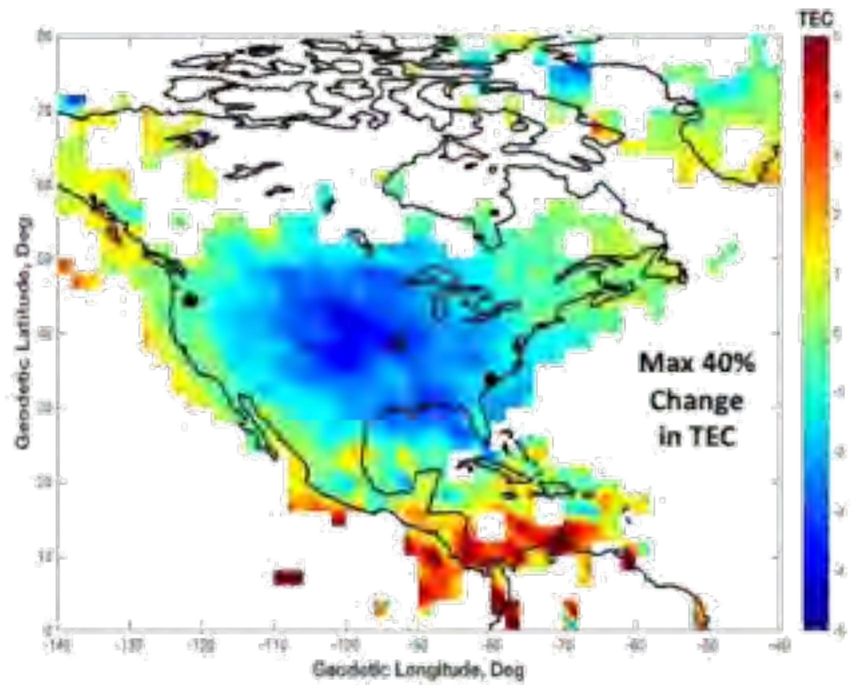
- Total Number of electrons between ground and GPS Satellite
- Measured by examining delay between two GPS Frequencies
- Traveling Ionospheric Disturbances
- Storm Effects
- Ionospheric Scintillations

Solar Eclipse

GNSS Vertical Total Electron Content

21 August 2017

Difference in TEC at 18:15 UT from start of solar eclipse at 16:45 UT



Support: NSF AGS-1242204, NASA NNX17AH71G

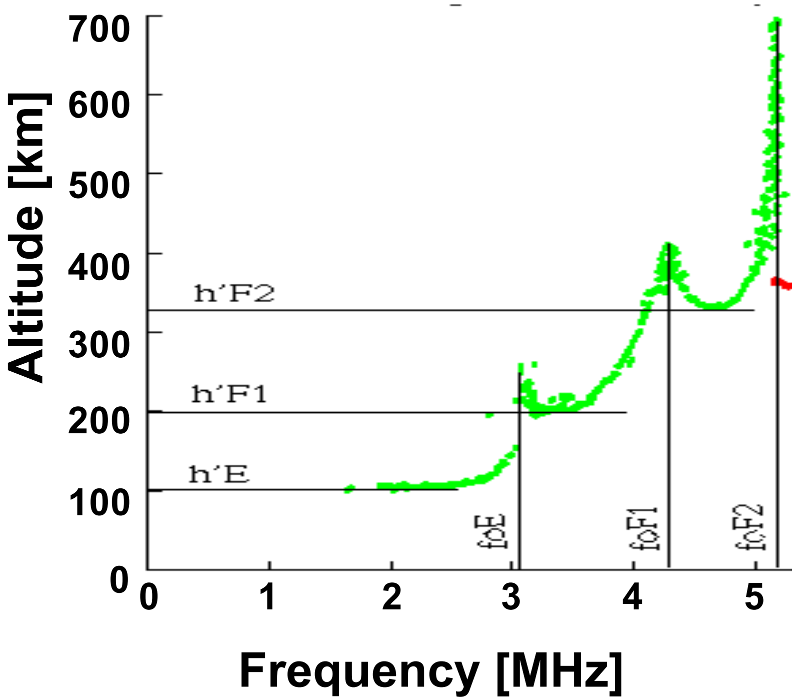
Courtesy of Anthea Coster

Ionosondes

- Vertical Incidence HF Radar
- Measure Plasma Density for bottomside Ionosphere

$$f_{pe} \approx 9\sqrt{n_e}$$

[Dr. Terry Bullett, W0ASP, U of Colorado]



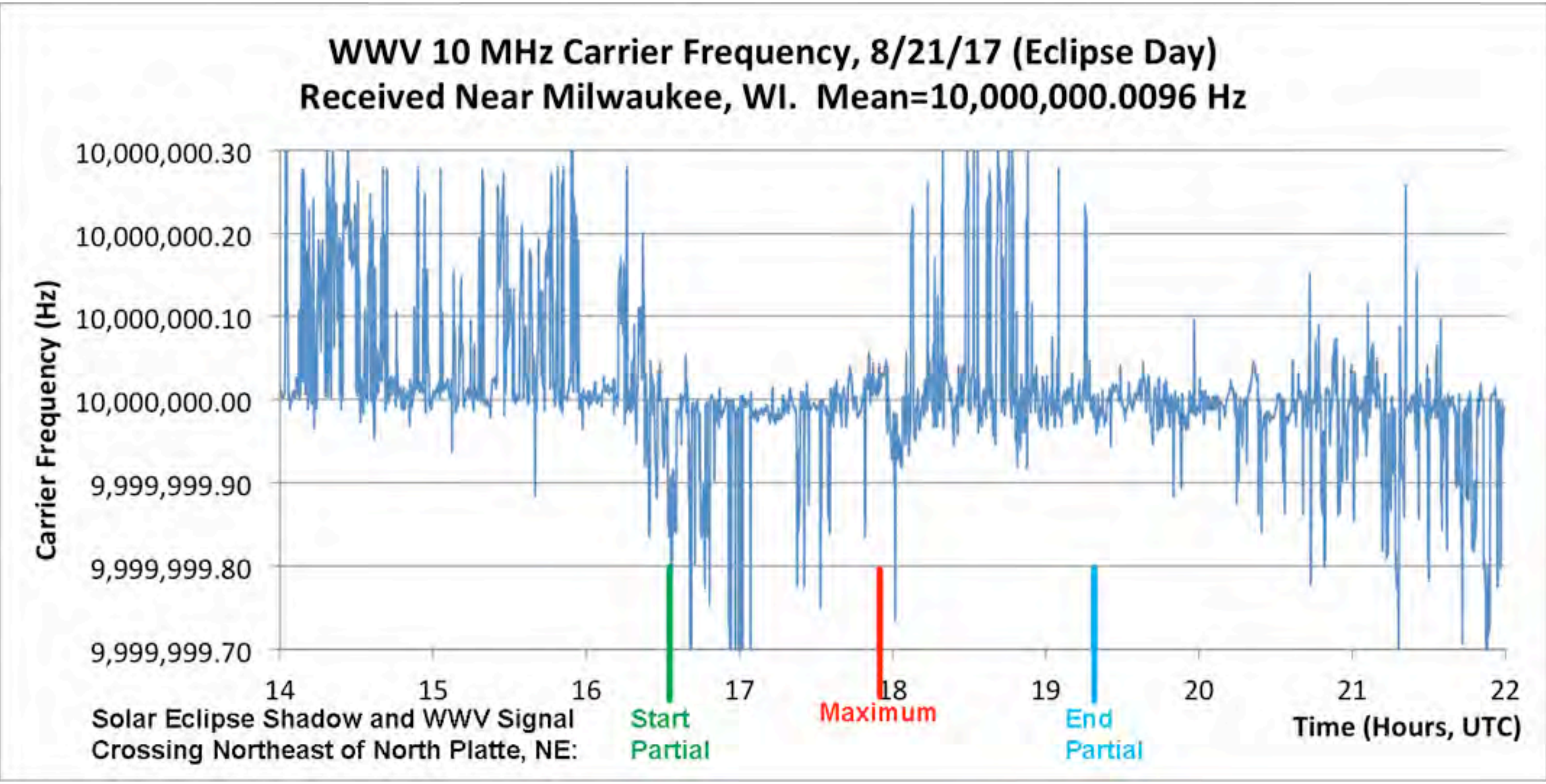
Riometer

- **R**elative **I**onopheric **O**pacity **M**eter
- Directly measures absorption of cosmic rays
- Indirectly measures electron density, particle precipitation
- Typically passive instrument 30-50 MHz

IRIS - Imaging Riometer for Ionospheric Studies in Finland (http://kaira.sgo.fi/)

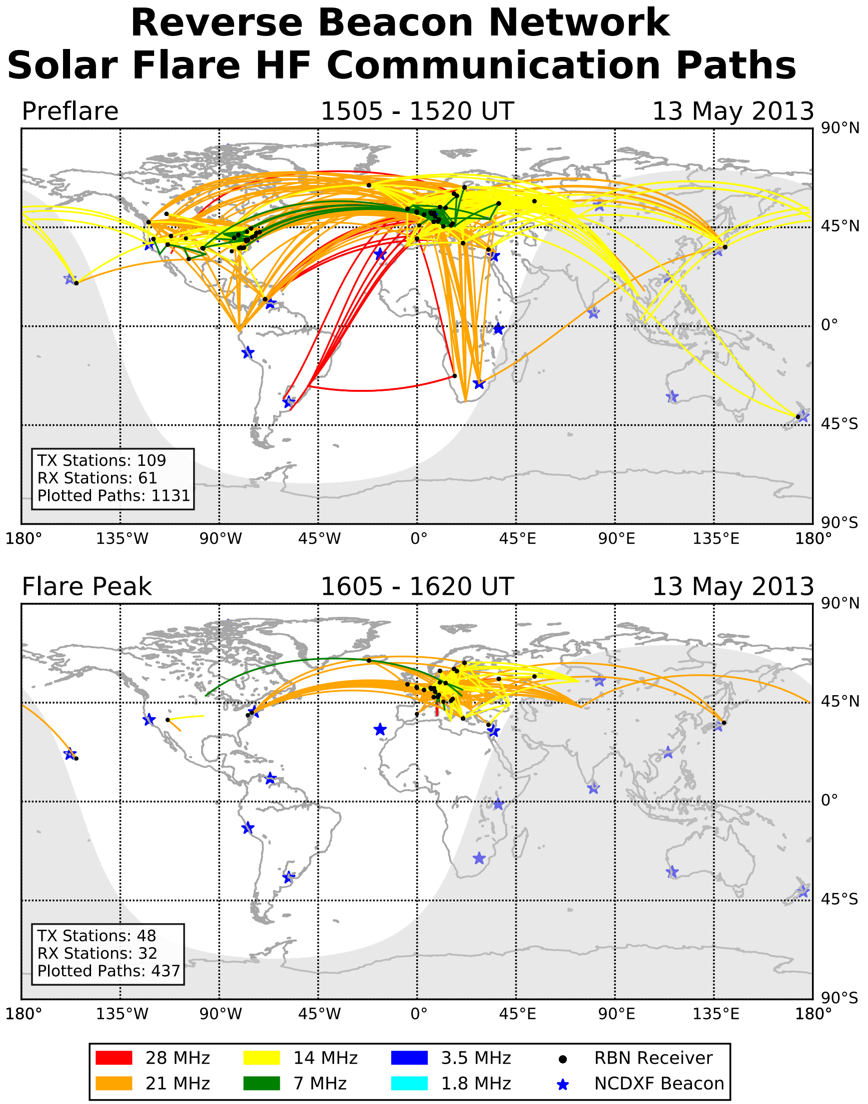
Photo: Derek McKay

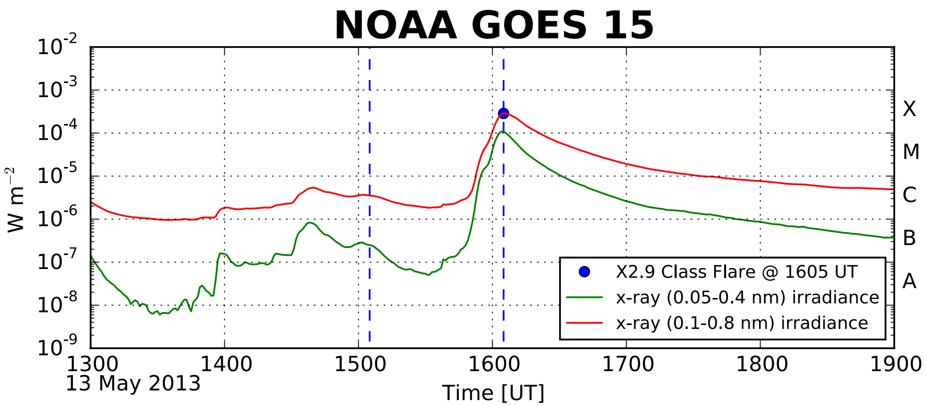
WWV/CHU Standards Monitor



Steve Reyer, WA9VNJ

RBN/PSKReporter/WSPRNet RX





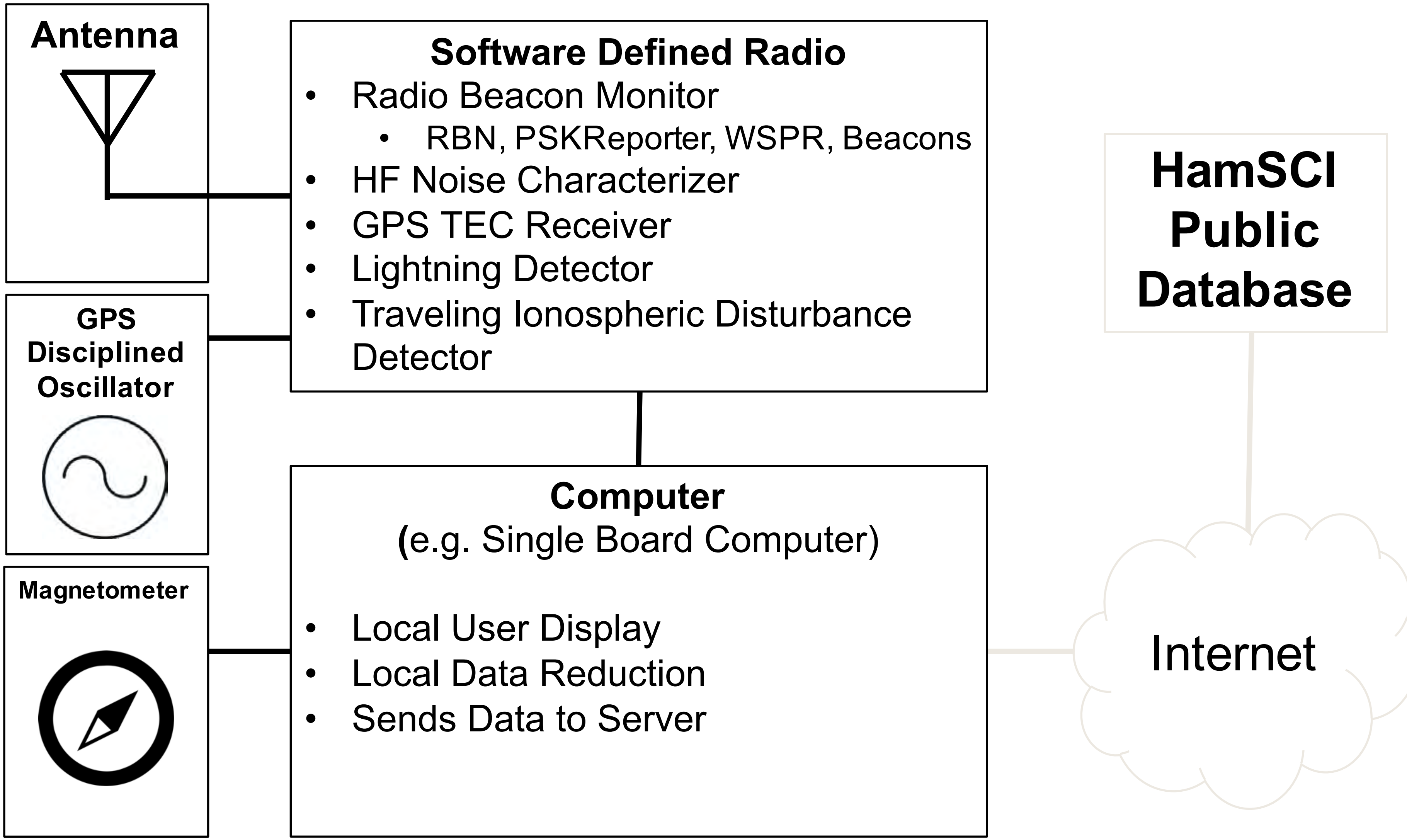
[*Frissell et al.*, 2014, *Space Weather*]

Lightning Detector

- Signatures from LF to VHF/UHF
- On HF, lightning noise can propagate long distances and disrupt communications

Photo: Jessie Eastland
(https://en.wikipedia.org/wiki/File:Desert_Electric.jpg)

Personal Space Weather Station



Some possible hardware…

Antenna
DXE ARAV3

?

GPSDO
Leo Bodnar

?

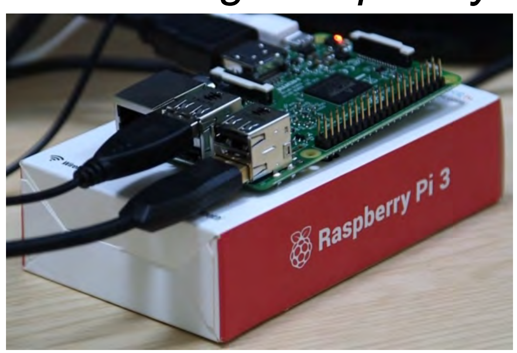
Magnetometer
British Geological Survey

?

Software Defined Radio
e.g. Red Pitaya

?

Computer
e.g. Raspberry Pi



?

HamSCI Public Database

Internet

Target Specifications

- Useful to ham radio, space science, and space weather communities.
- $100 to $500 (??) price range (accessible)
- Modular Instrument Design
  - Easy ability to add or remove instruments, especially in software architecture
- Small footprint
- Nice User Interface/Local Display
- Standard format to send data back to a central repository
- Open community-driven design

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Networking/Infrastructure

- App Ecosystem
  - Publish/Subscribe?
- Data & Science Transfer
  - Near real-time continuous monitoring
  - Run Coordinated Campaign
  - Request raw data from clients

    (Use ring buffer for past data)
- Retain ability to operate without Internet

Benefits to Owner

- PSWxS should also be useful to the local user/owner.
- Local display
- Web interface
- Ideas
  - Identify which bands are active
  - Characterize local RF environment
  - Provide visual display of instrument data (both past and present)
  - Act as a general receiver

HF Receiver Instrument

Where do we start?

- **General purpose HF Receiving Instrument.**
- **Why?**
  - Few networks of widespread scientific HF radio receivers currently exist.
  - “Signals of opportunity” available.
  - Extremely flexible research tool.
  - Directly applicable to ham radio.
  - Radio is TAPR’s Bread and Butter ☺

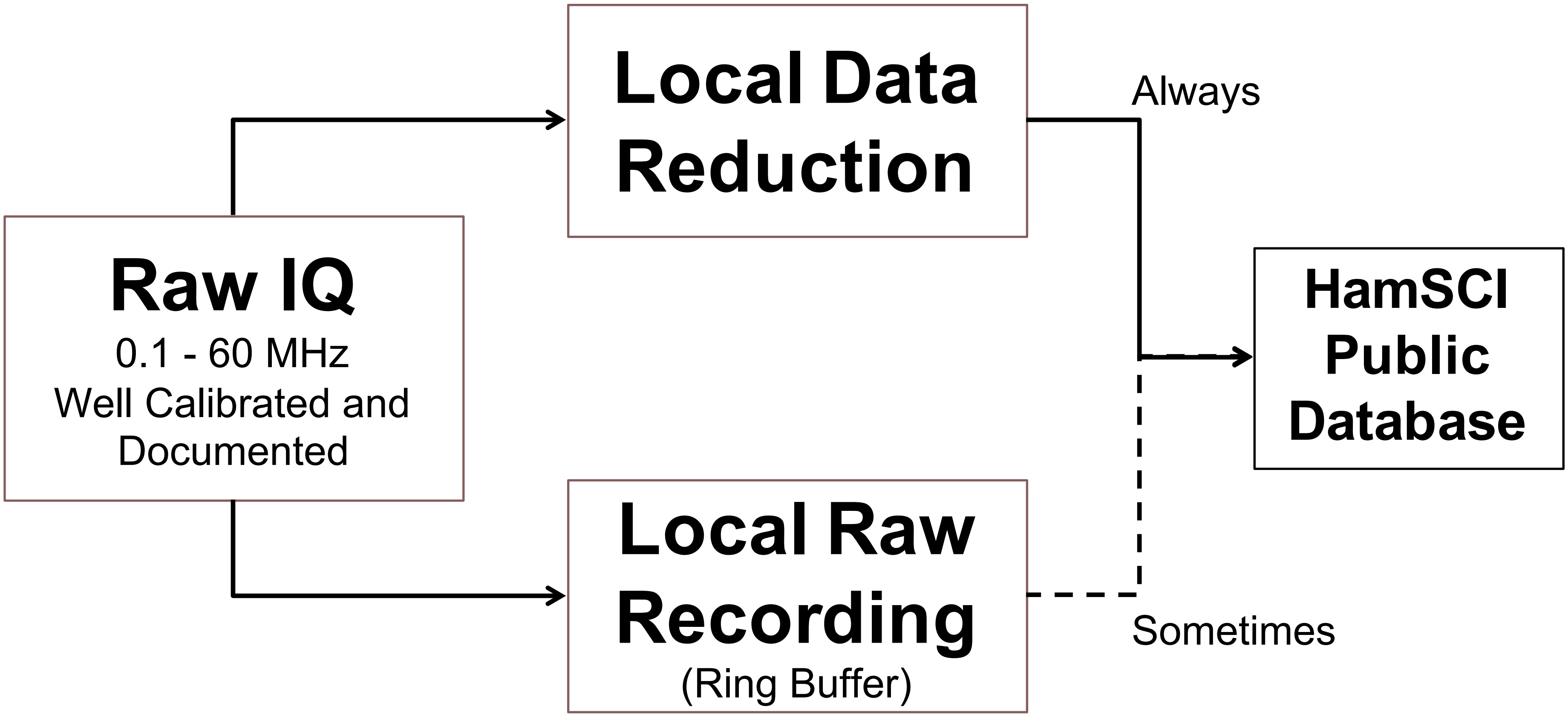
Where do we start?

- General purpose HF Receiving Instrument.

Raw IQ
0.1 - 60 MHz
Well Calibrated and
Documented

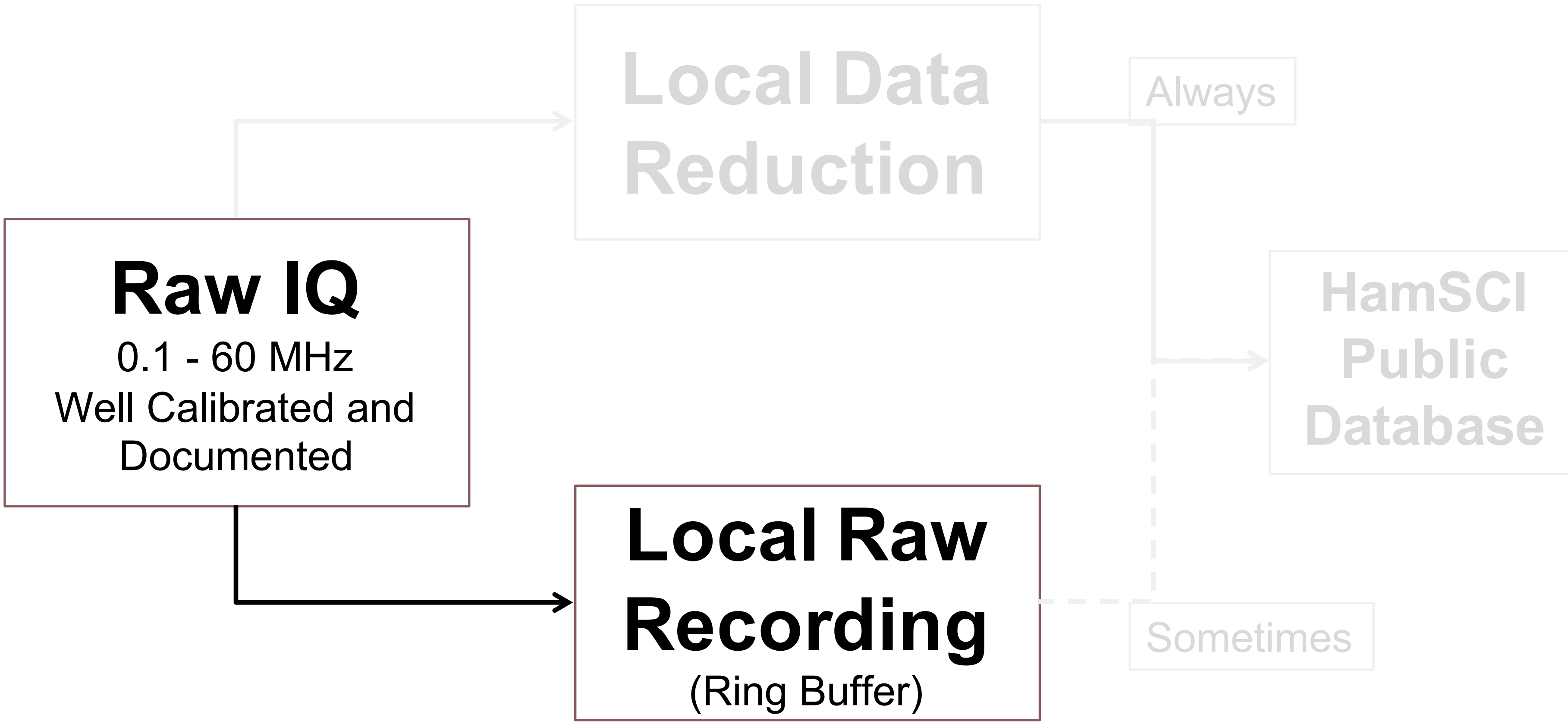
Where does this go?

- General purpose HF Receiving Instrument.



Where does this go?

- General purpose HF Receiving Instrument.



Quality Raw IQ is the Foundation

- Quality HF raw IQ → all downstream research and operational products.

HF Receiver Specifications

What I Want
Raw Spectrum from DC to Daylight
Multiple Input Channels
Absolute amplitude-calibrated receiver (i.e. Field Strength Meter)
Calibrated system noise
Accurate frequency resolution
Accurate timing and location (enable interferometry)
Known antenna system characteristics
Infinite recording storage capacity

HF Receiver Specifications

What I Want	Reality/Implementation
Raw Spectrum from DC to Daylight	• 8-192 kHz Slice Receivers Across HF
Multiple Input Channels	• 2 Input Channels
Absolute amplitude-calibrated receiver (i.e. Field Strength Meter)	
Calibrated system noise	• Inclusion of local, known noise source
Accurate frequency resolution	• To accuracy provided by GPSDO
Accurate timing and location (enable interferometry)	• To accuracy provided by GPSDO
Known antenna system characteristics	• Provide recommendations to user • Make easy for user to add metadata
Infinite recording storage capacity	• Ring buffer • Ability to request periods of raw data

Do things like this exist today?

- Not at a low to moderate cost
- Ettus has the performance, but not cost effective for this application
  - Lots of choices of daughterboards/frequencies
  - Ethernet interface
  - Inputs for external 10 MHz and PPS
  - Time stamps data

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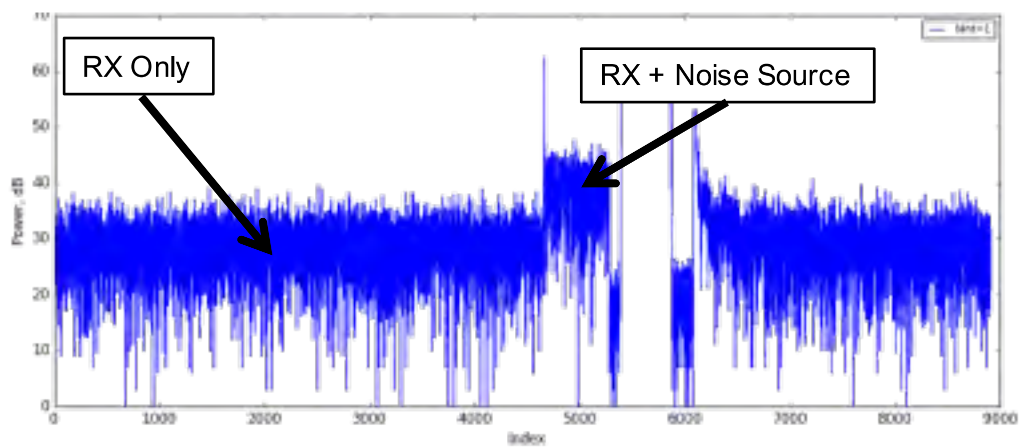
Measuring Noise

- Jim Frazier KC5RUO talked about issues of understanding noise in FT8/JT65/JT9… it's not easy!
- Exact numbers are less important (e.g. a wide variety of bandwidths can be used for the noise measurement – **as long as you know what you used!**)
- Standardization and documentation is **very** important.
- Example noise sources
  - Atmospheric Noise
  - Lightning Noise
  - Instrumental (self-generated noise)
  - Cosmic noise

Measuring Noise

- Calibrated Local Noise Source
- $P = K_B T (BW)$
- Could a reference noise source be integrated on the receiver board?

Millstone Hill ISR Radar Receiver



2017 Noise Source Simple Spectrum External Generator Tracking SMA Source + Case

Condition: **New**

Sale ends in: 05d 13h 50m

Quantity: 1 2 available / 239 sold

Was: ~~US $16.00~~

You save: $0.80 (5% off)

Price: **US $15.20**

Buy another

Add to cart

Best Offer:

Make Offer

Add to watch list

100% buyer satisfaction	239 sold	More than 98% sold

Bucks You'll earn **$0.15** in eBay Bucks. See conditions

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Importance of Metadata

- RF Instrument Metadata
  - Center Frequency
  - Bandwidth
  - Impulse Response
  - Sampling Fidelity (e.g. # of bits)
  - Voltage to ADC Calibration Number
  - Timestamp (UTC Locked)
- Station Metadata
  - Station ID
  - Station Configuration
  - Geographic Location

MIT Haystack DigitalRF Software

- Provides a solution for storing all metadata with IQ data
- Uses standardized HDF5 data format
- GnuRadio Source and Sink Blocks
- Open Source

https://github.com/MITHaystack/digital_rf

DIGITAL RF

Project Goals and Timeline

Future Developments

- Software/Network Architecture
  - Very Near Future
  - Network Security

- Transmitter?
- Add instruments?
- Experimental features?

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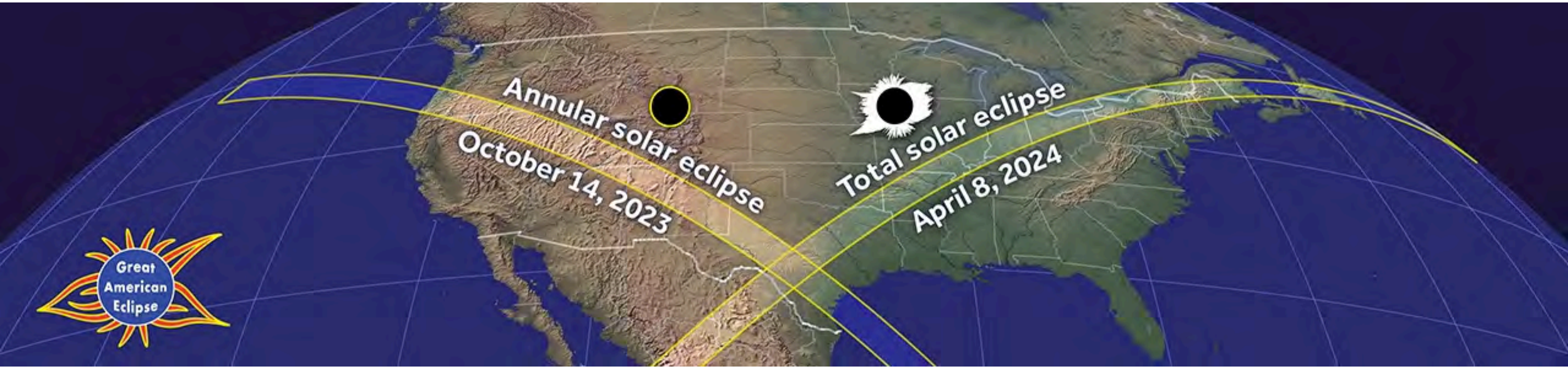
Eclipses 2023 and 2024

- Eclipses in 2023 and 2024 are great targets for the Personal Space Weather Station
- Example Science Goal
  - Look for TID wave signatures in both GPS-TEC and the HF receiver?



[https://www.greatamericaneclipse.com/]

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Timeline

Yr	Date	HF Rx Hardware	Station Software	Server Software
1	HamSCI 2019	Specifications & Initial Design		
	TAPR 2019	Prototype	Interface and Data Specification	Interface and Database Specification
2	HamSCI 2020		Data Structure Implementation	Database Implementation
	TAPR 2020	Beta Version	Prototype Science/Eng Products	Aggregate Data Test Science Products
3	HamSCI 2021		Refine Science/Eng Products	Refine Science Products
	TAPR 2021	Field Tests	Field Tests	Field Tests
4	HamSCI 2022	Review & Refine	Review & Refine	Review & Refine
	TAPR 2022	Manufacture		
5	HamSCI 2023	Distribute and Deploy		
	TAPR 2023	**Annular Eclipse**		
6	HamSCI 2024	**Total Eclipse**		
	TAPR 2024			Analyze Data

Thank you!

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