A Survey of Terrestrial Radio Research Techniques

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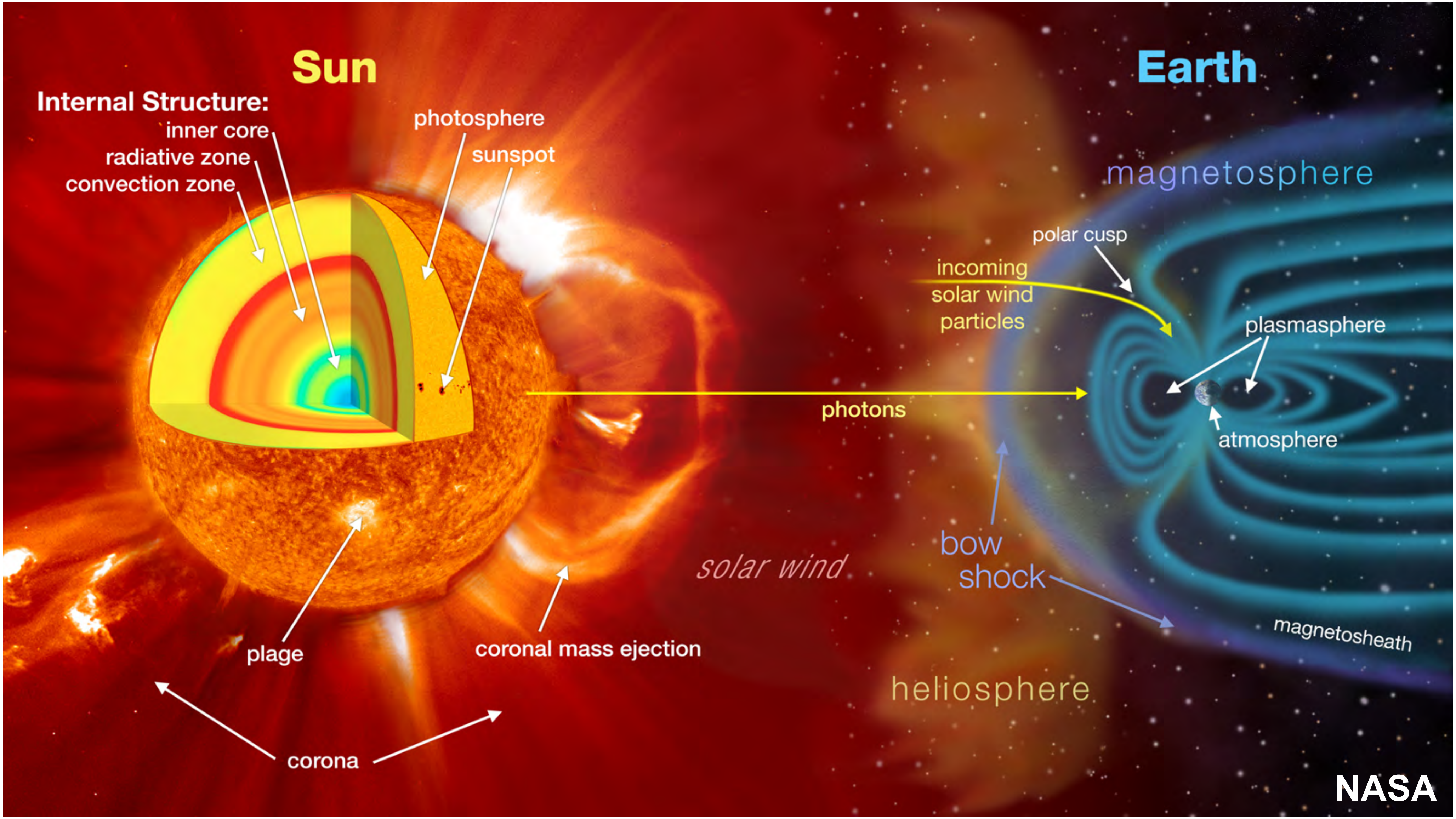
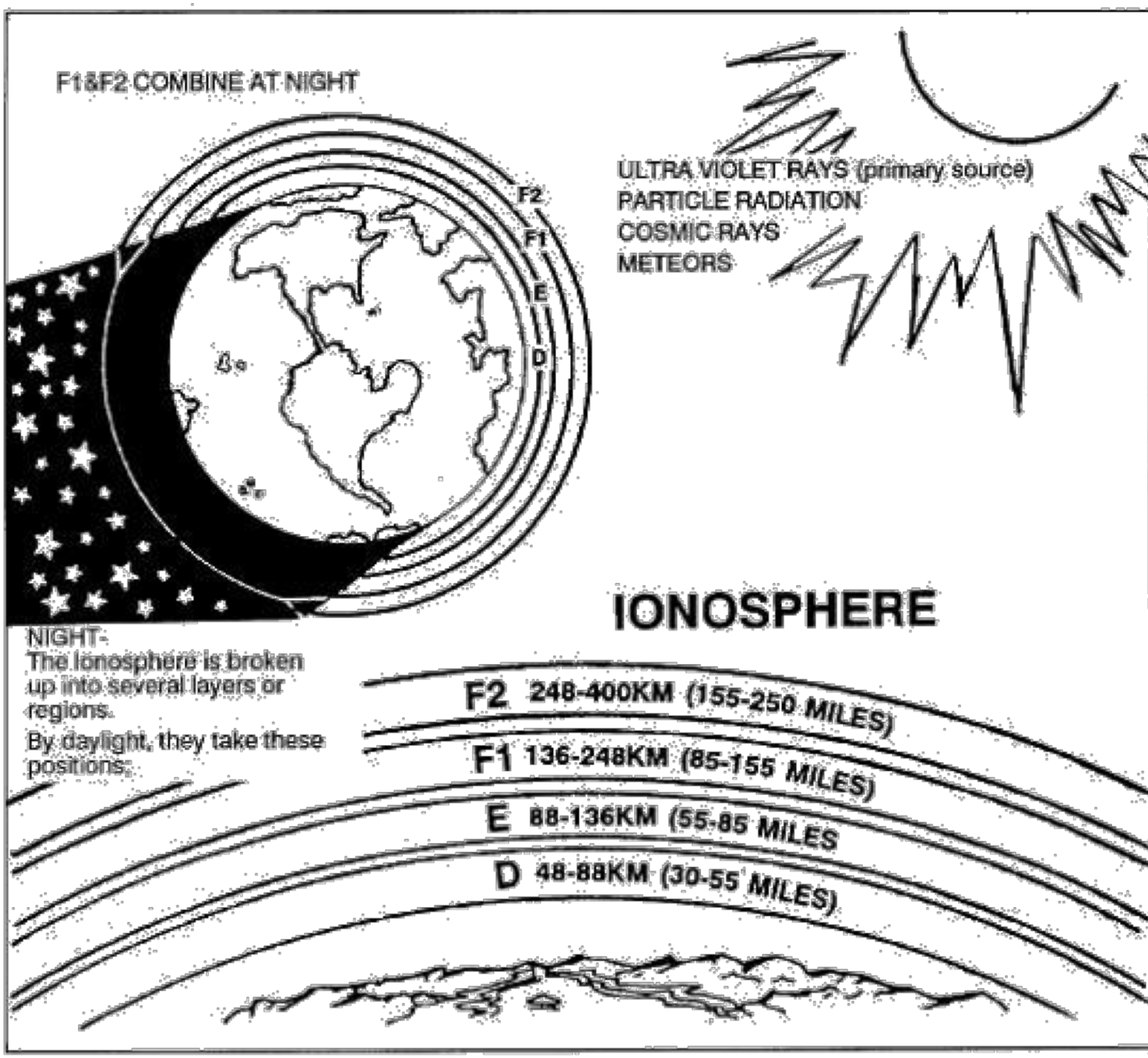
Solar-Terrestrial Environment



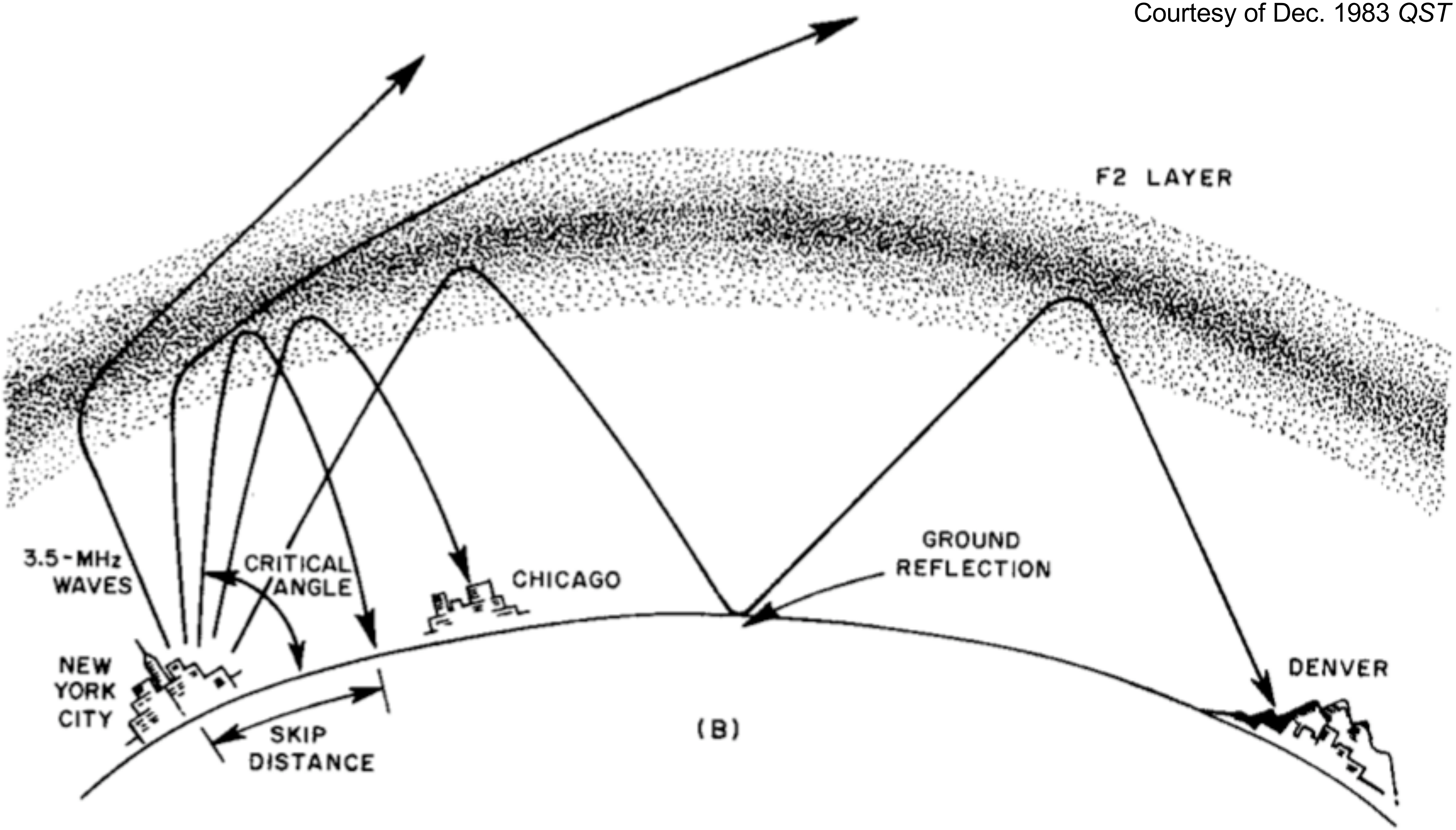
Ionosphere



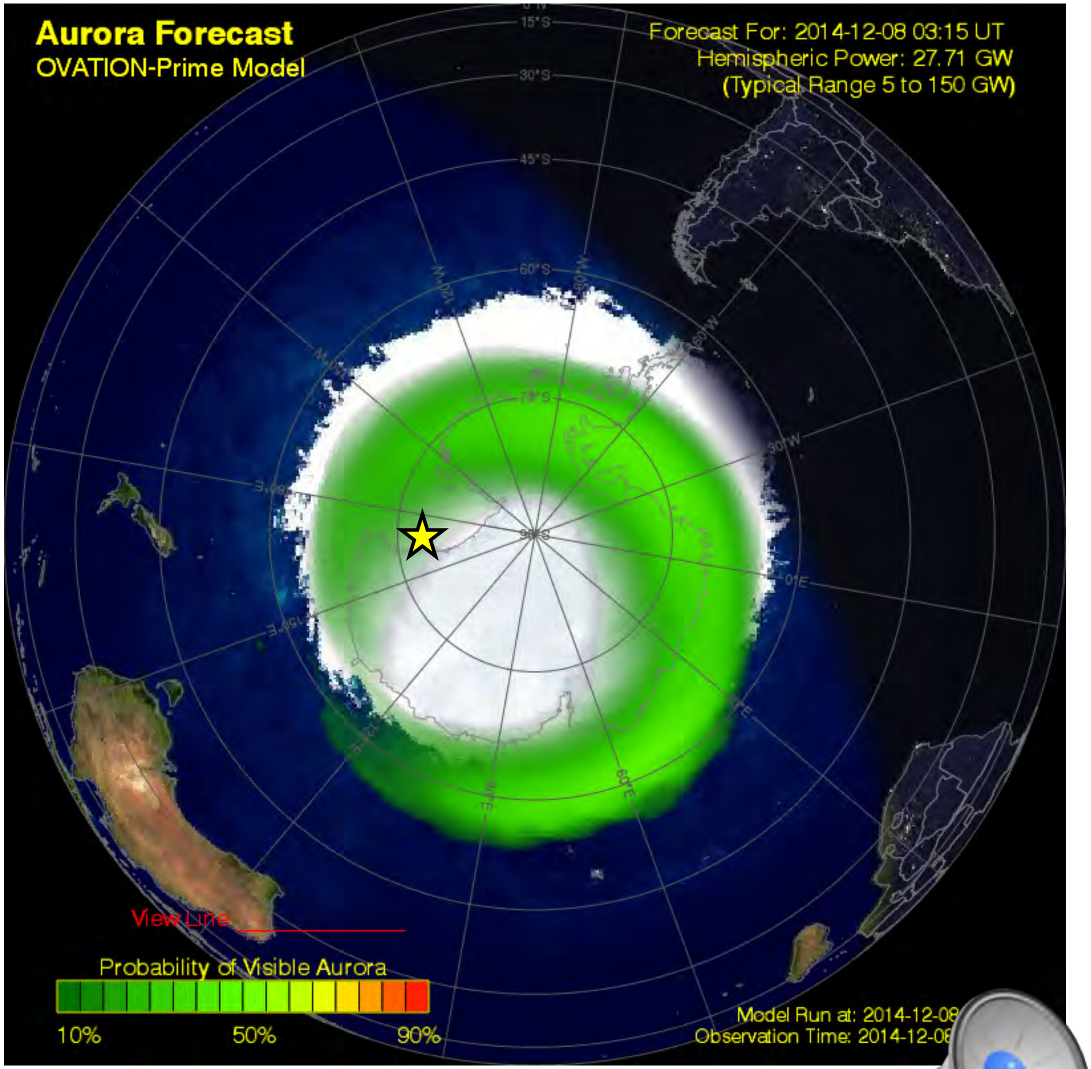
F1&F2 COMBINE AT NIGHT
F2
F1
E
D
ULTRA VIOLET RAYS (primary source)
PARTICLE RADIATION
COSMIC RAYS
METEORS
IONOSPHERE
NIGHT-
The Ionosphere is broken up into several layers or regions.
By daylight, they take these positions;
F2 248-400KM (155-250 MILES)
F1 136-248KM (85-155 MILES)
E 88-136KM (55-85 MILES
D 48-88KM (30-55 MILES)

Skip Propagation

Courtesy of Dec. 1983 *QST*



Space Weather and Ham Radio



20141227 0746 UT Aurora @ KC4USV 14010 kHz

Ionospheric Radio Instruments

- Ionosondes
- Riometers
- GPS Total Electron Content (GPS-TEC)
- GPS Scintillation Receivers
- Incoherent Scatter Radars
- SuperDARN Radars
- Ionospheric Heaters
- Signals of Opportunity

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Ionospheric Radio Wave Propagation

The Plasma Frequency

If the electrons in a plasma are perturbed (assuming the ions are much more massive, so they remain stationary), the electrons oscillate about their equilibrium position at frequency known as the plasma frequency.

$$f_p = \sqrt{\frac{n_e e^2}{2\pi m_e \varepsilon_0}} \approx 9 n_e^{1/2} kHz$$

(n_e in cm^{-3})

So if $n_e = 10^6\ cm^{-3}$, $f_p = 9$ MHz

Electromagnetic Waves in a Plasma

An electromagnetic wave can only propagate through a plasma if its frequency is greater than the local plasma frequency; then a wave packet or signal travels at the group velocity given by:

$$v_{gp} = c\sqrt{1-\left(f_p \big/ f_{wave} \right)^2} \leq c = \text{the speed of light}$$

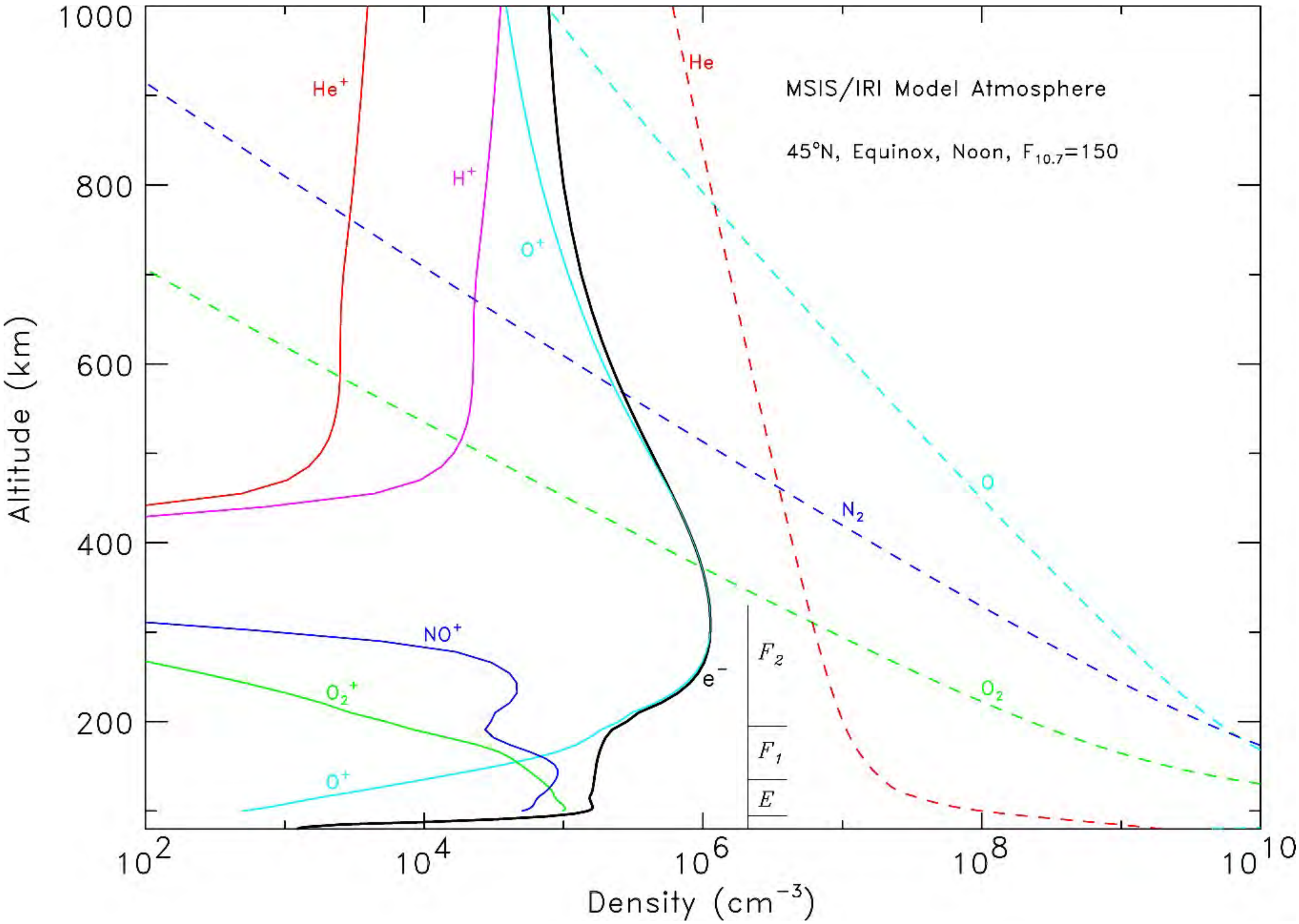
The total delay in a signal is proportional to the column number density of electrons along the signal path – the total electron content or TEC

Reflection of Radio Waves

If an electromagnetic wave propagates into a plasma with increasing plasma density, its group velocity will get progressively slower as the plasma frequency increases to near the wave frequency. The wave will reflect at the point where the wave frequency equals the plasma frequency, i.e. where

$$f_{wave} = f_p = \sqrt{\frac{n_e e^2}{2\pi m_e \varepsilon_0}} \;;\; 9n_e^{1/2} kHz \qquad (n_e \text{ in cm}^{-3})$$

Thermospheric/Ionospheric Densities

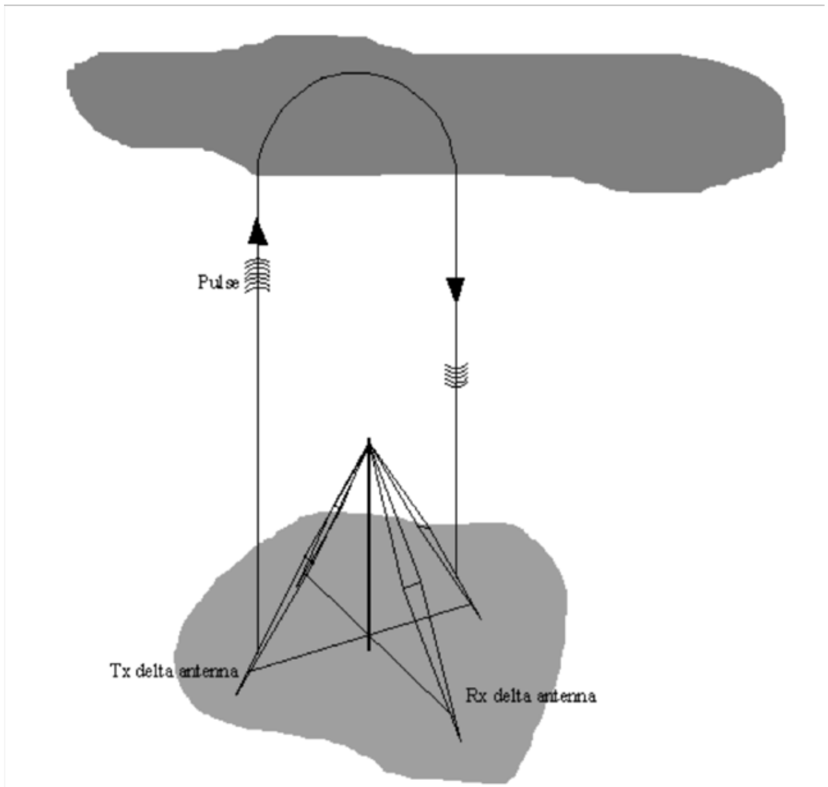


Ionosondes

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

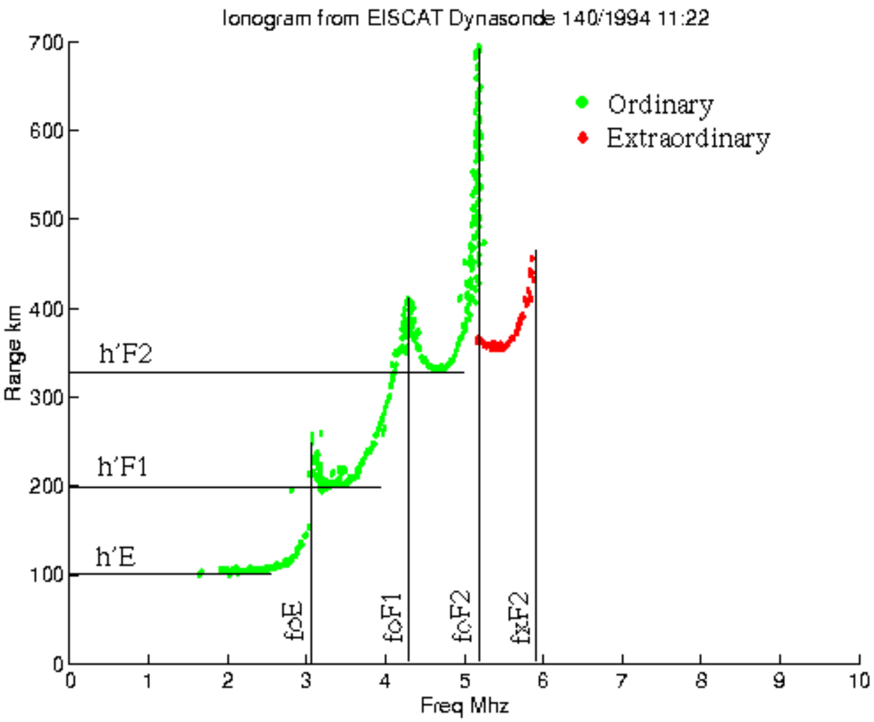
Ionosondes & Ionograms

Principle of an "ionosonde"



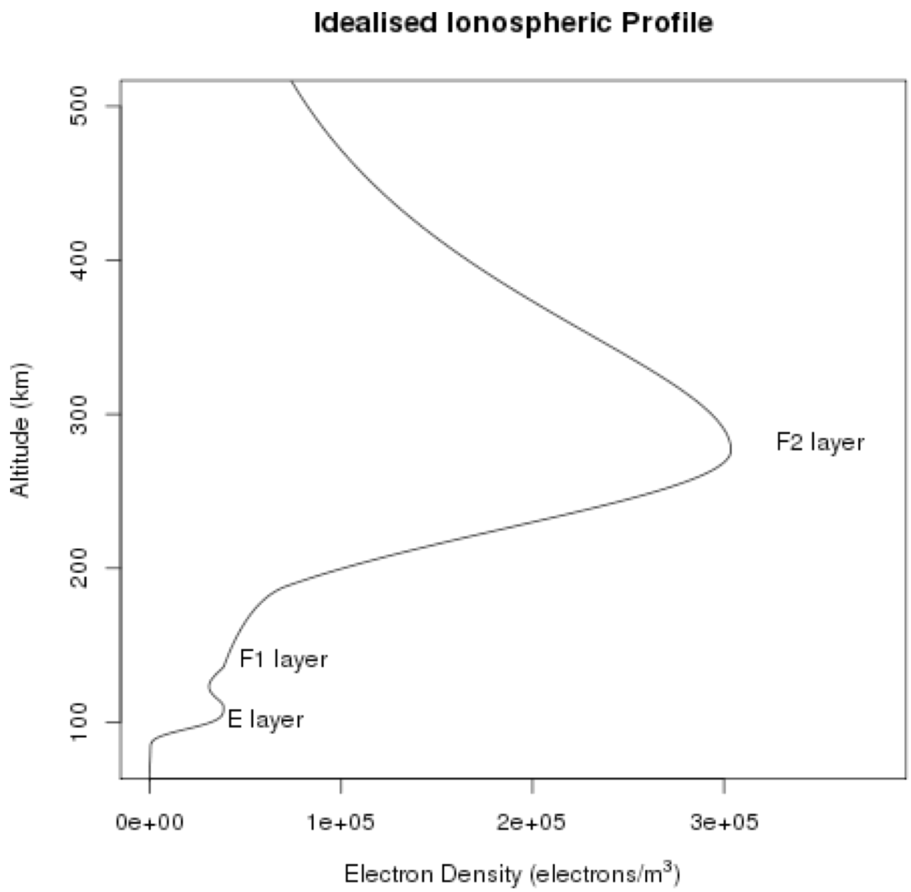
an "ionogram"

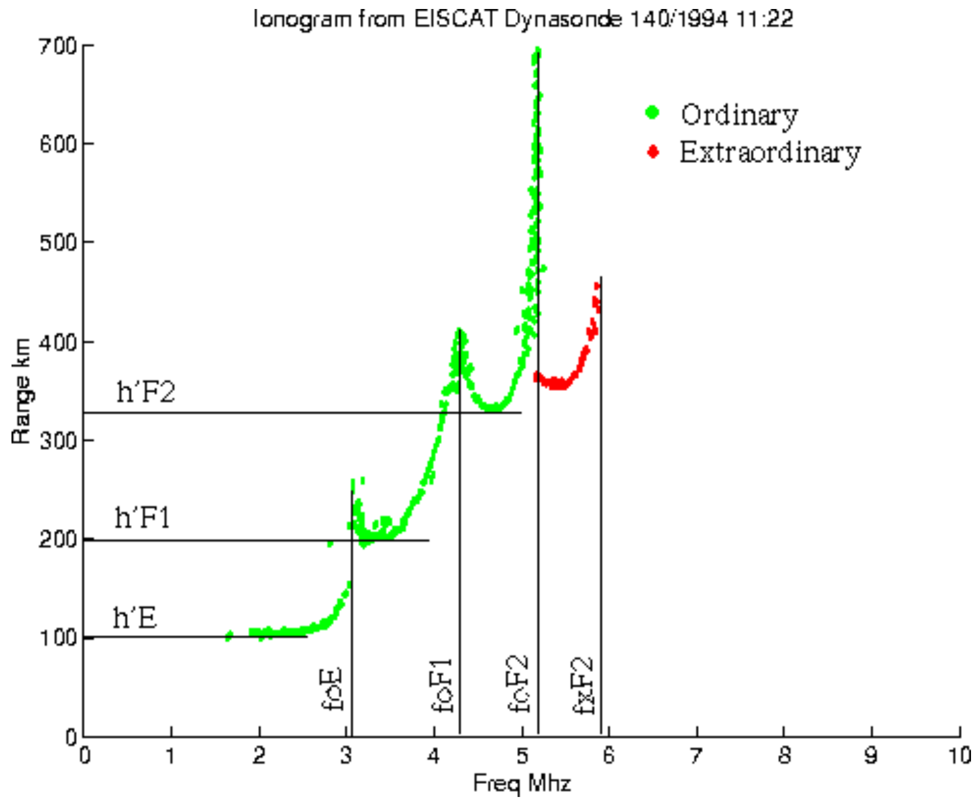
Echo time converted into a distance



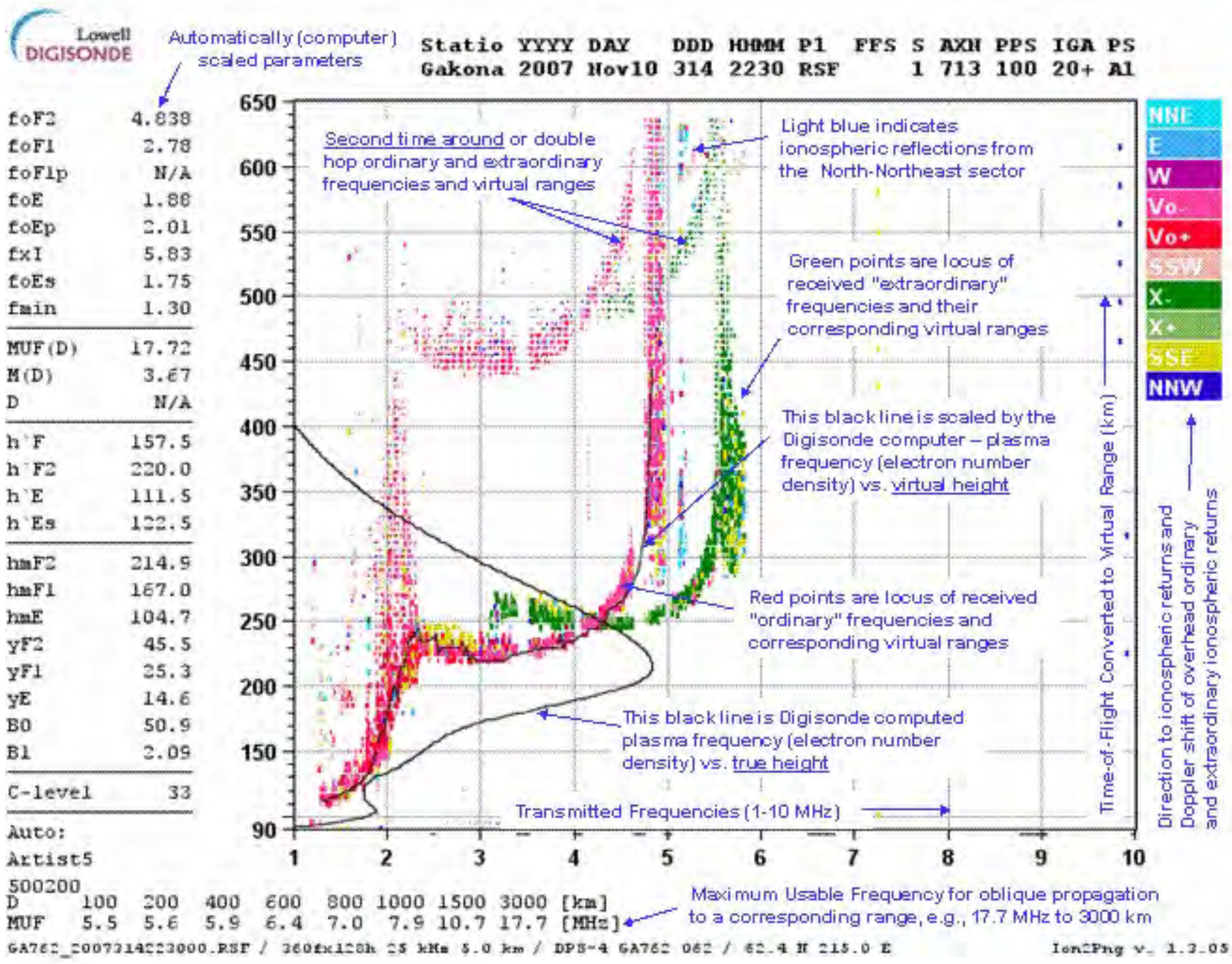
Transmission Frequency

Electron Profile vs. Ionogram

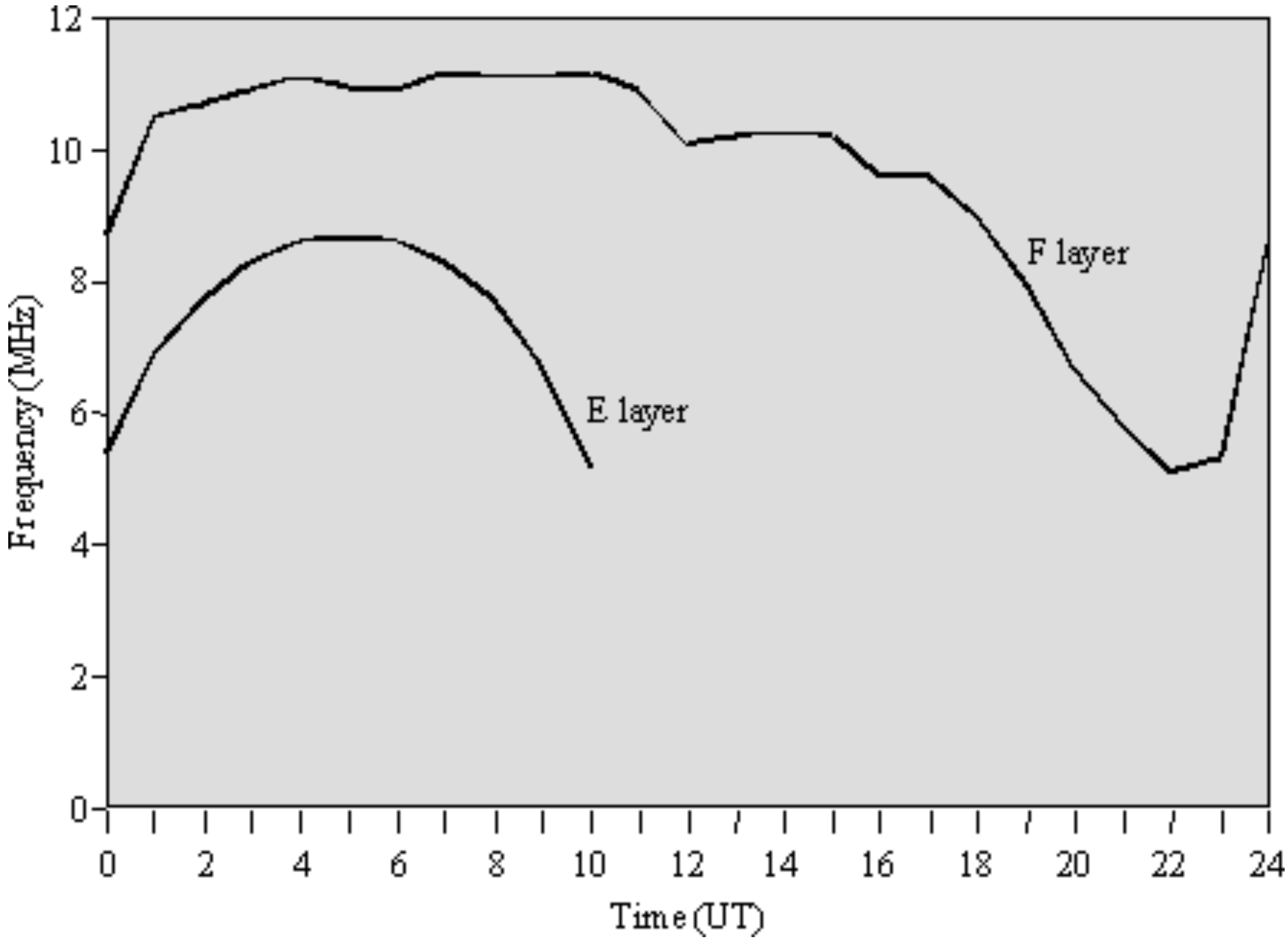




Modern Digital Ionogram (Gakona, AK)

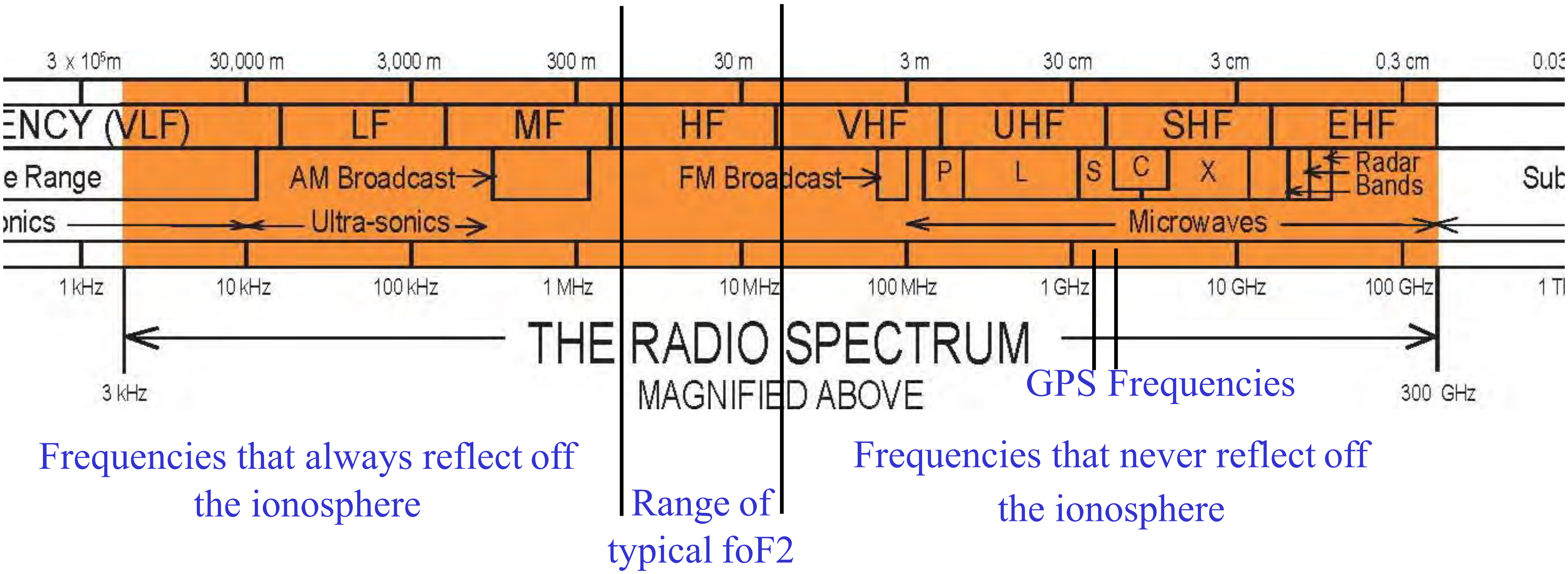


E & F Layer Diurnal Variation

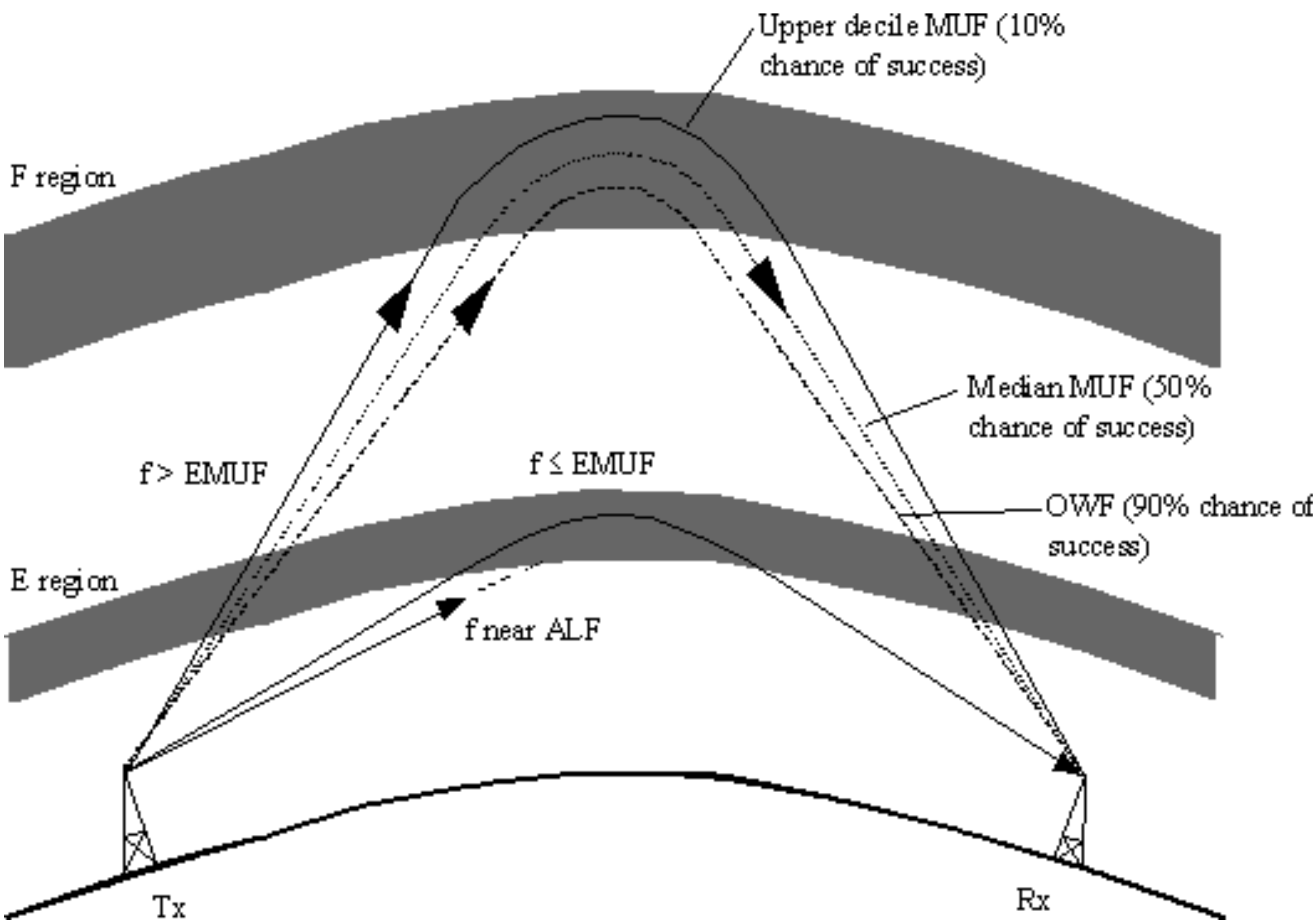


The source of this material is at http://www.ips.gov.au/

Radio Waves and the Ionosphere



Maximum Usable Frequency (MUF)

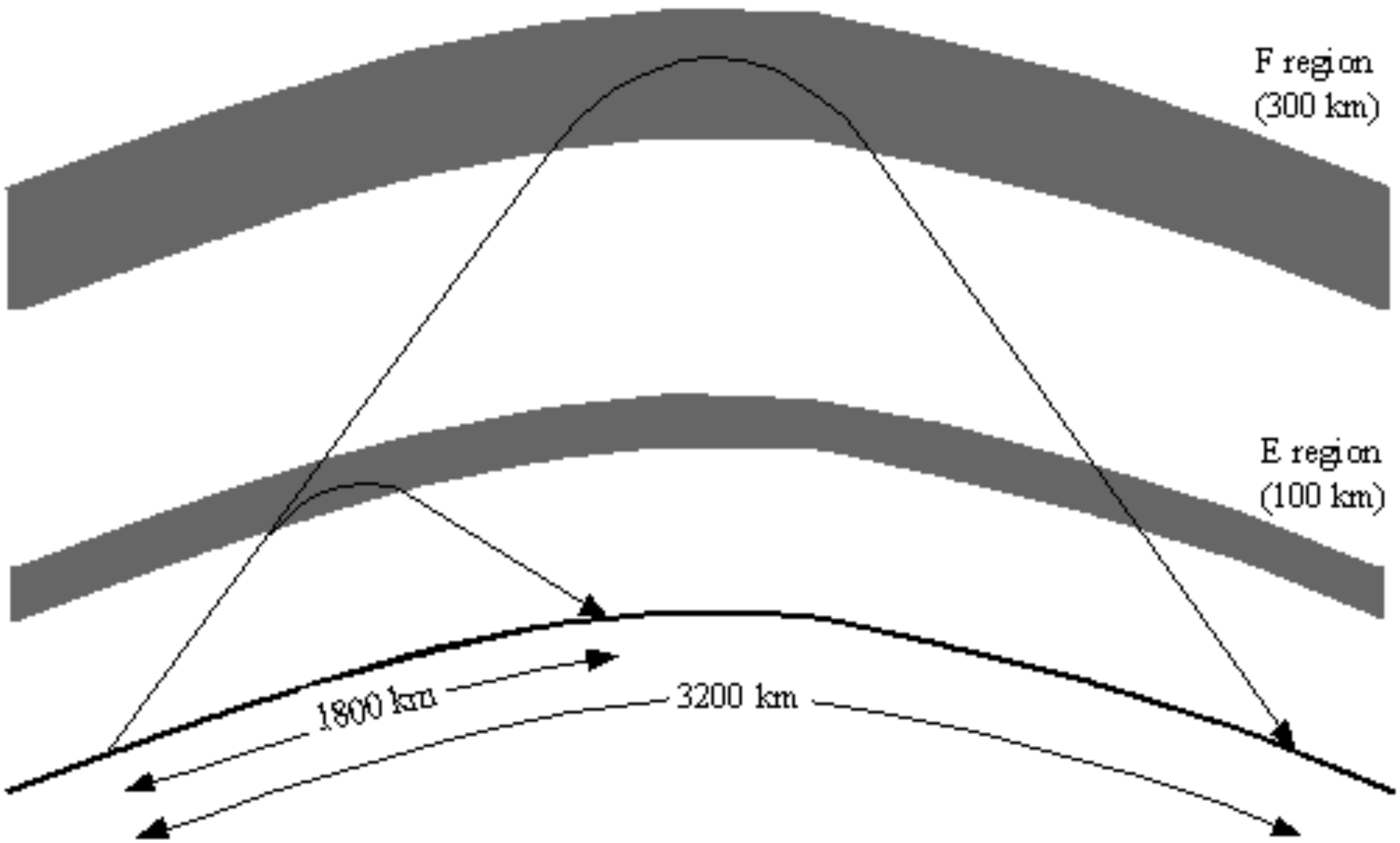


The source of this material is at http://www.ips.gov.au/

ALF = Absorption Limiting Frequency, OWF = Optimum Working Frequency

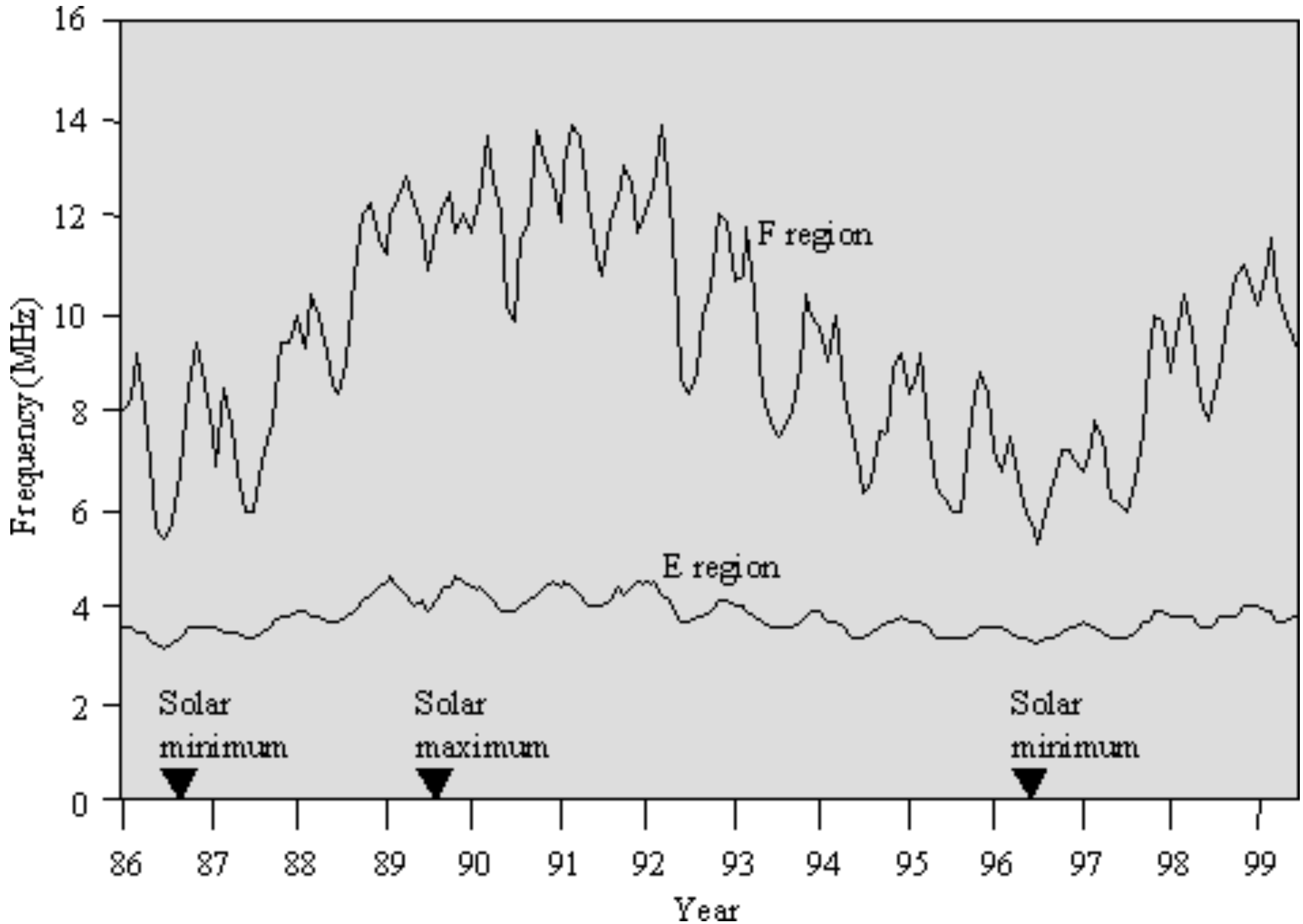
Hop Length

"Hop Length" depends on frequency and reflection height

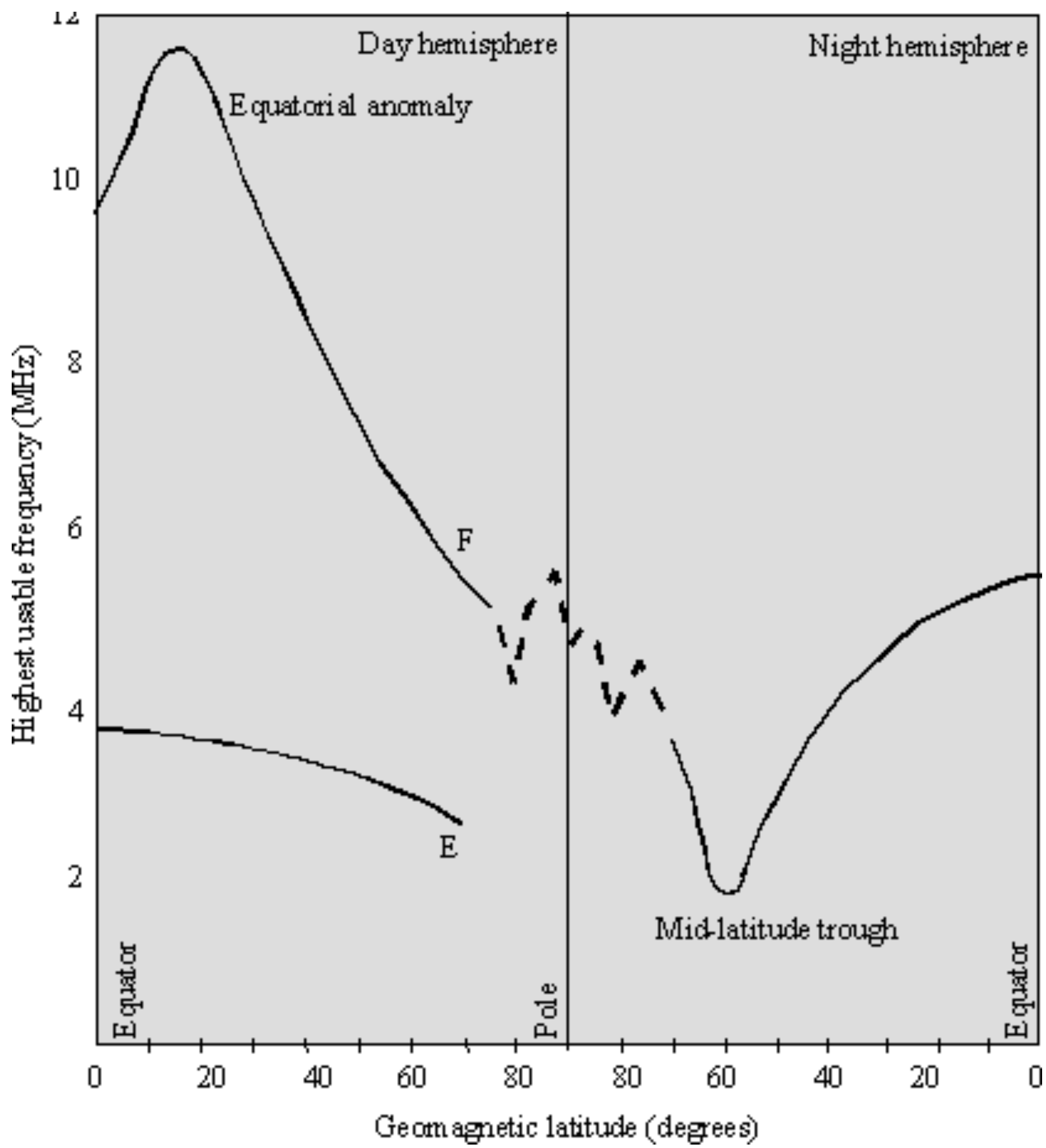


The source of this material is at http://www.ips.gov.au/

Ionospheric Frequencies Over a Solar Cycle



Diurnal and Latitudinal Dependence



E and F-region reflecting frequencies depend upon magnetic latitude differently from day to night

Four Ways by which Space Weather affects Radio Communications

Affect GPS Signals

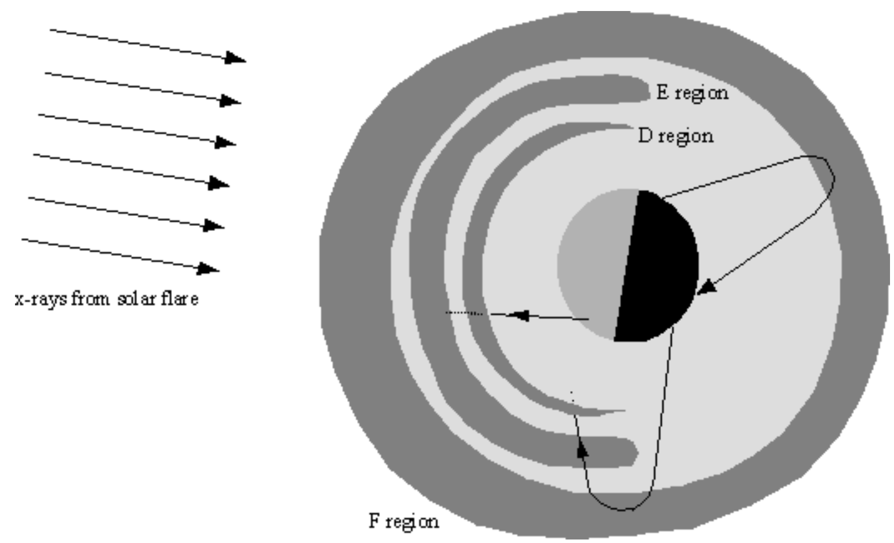
- Radio Absorption: signals in the HF band (Short Wave) can be absorbed (attenuated) by additional ionization in the lower ionosphere caused by solar X-rays (sunlit ionosphere) or energetic particles (SEP) (high latitudes)
- Scintillations: Naturally occurring instabilities in the ionosphere (sporadic-E, spread-F) can scatter and phase-mix signals causing loss of signal
- Masking: Naturally generated solar radio waves can mask man-made signals
- Phase and Group Delay: Introduces range errors

- All effects on radio communication depend upon frequency of wave and wave path

HF Absorption

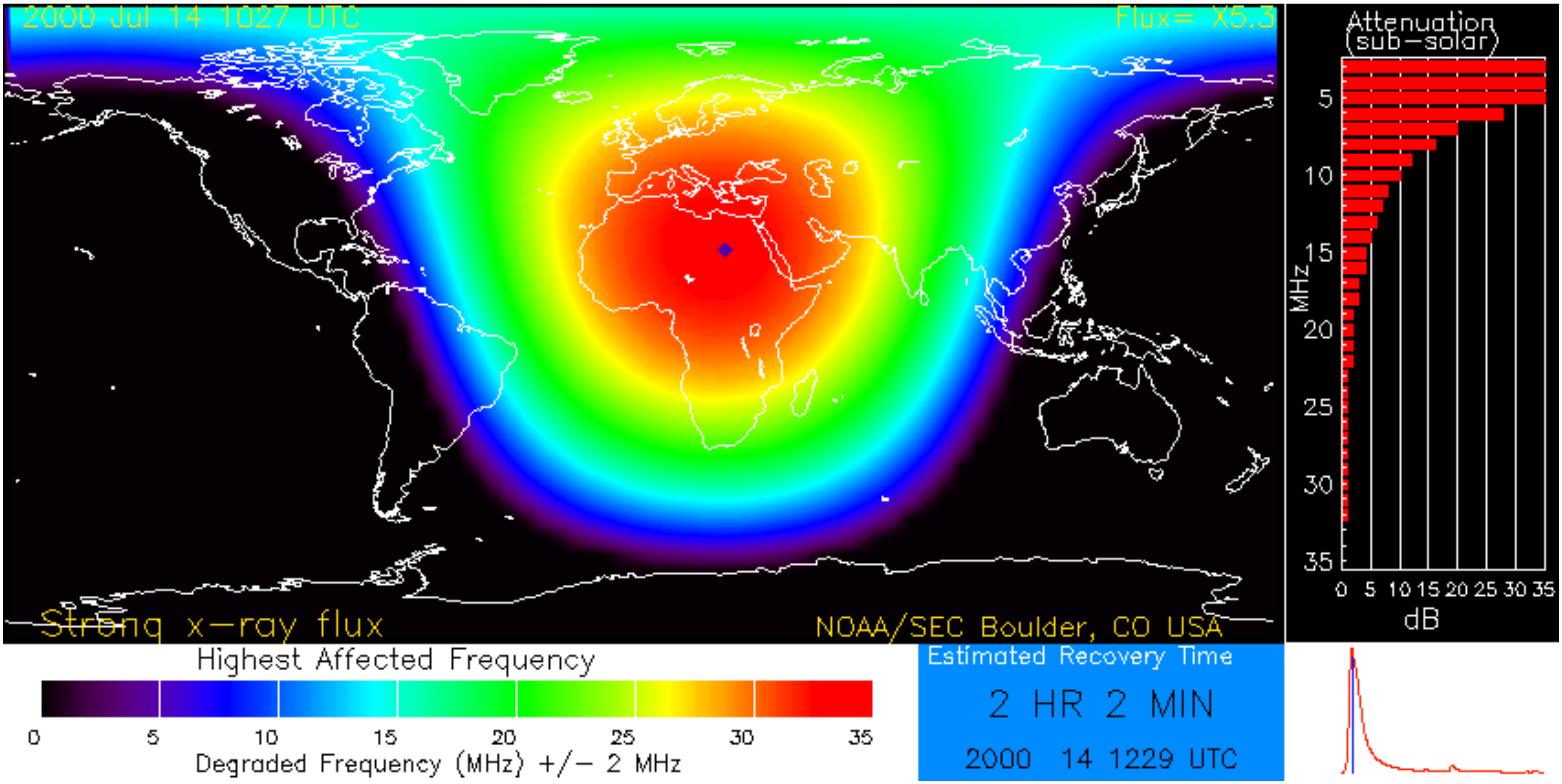
HF Radio Absorption

Short wave fade-outs (SWFs) also called daylight fade-outs or **sudden ionospheric disturbances (SIDs).** Solar radiation, either **X-rays** from large solar flares (dayside) or **SEP** (polar regions) cause increase ionization in the D region which results in greater absorption of HF radio waves. If the event is large enough, the whole of the HF spectrum can be rendered unusable for a period of time. Flares, and hence fade-outs are more likely to occur around solar maximum and in the first part of the decline to solar minimum.

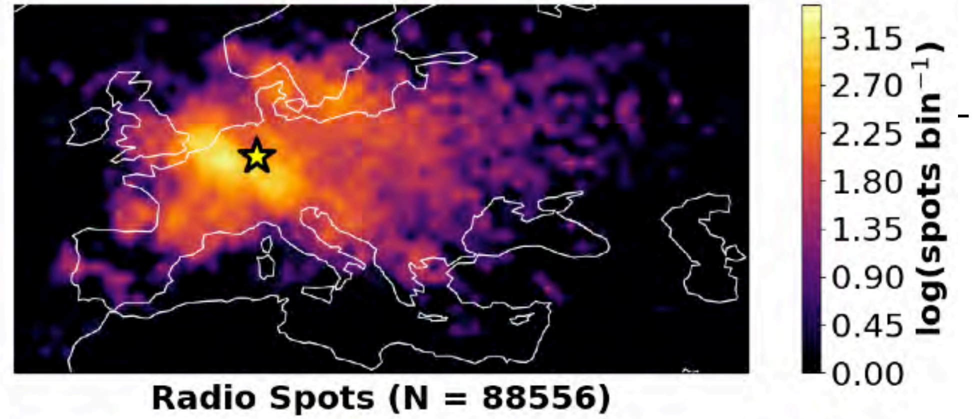


NOAA D-RAP

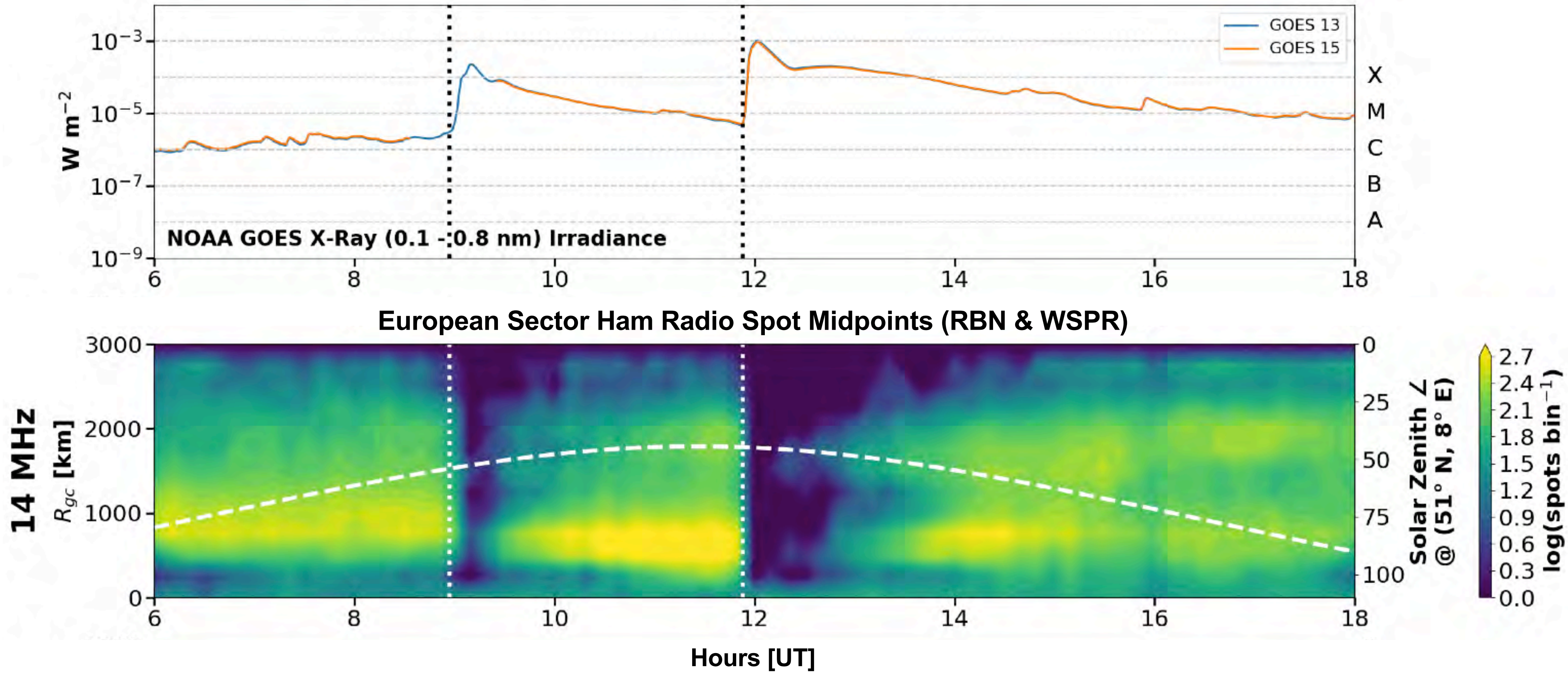
NOAA/SEC D-Region Absorption Prediction
Bastille Day X-ray event: 2000 Jul 14 1230 UTC



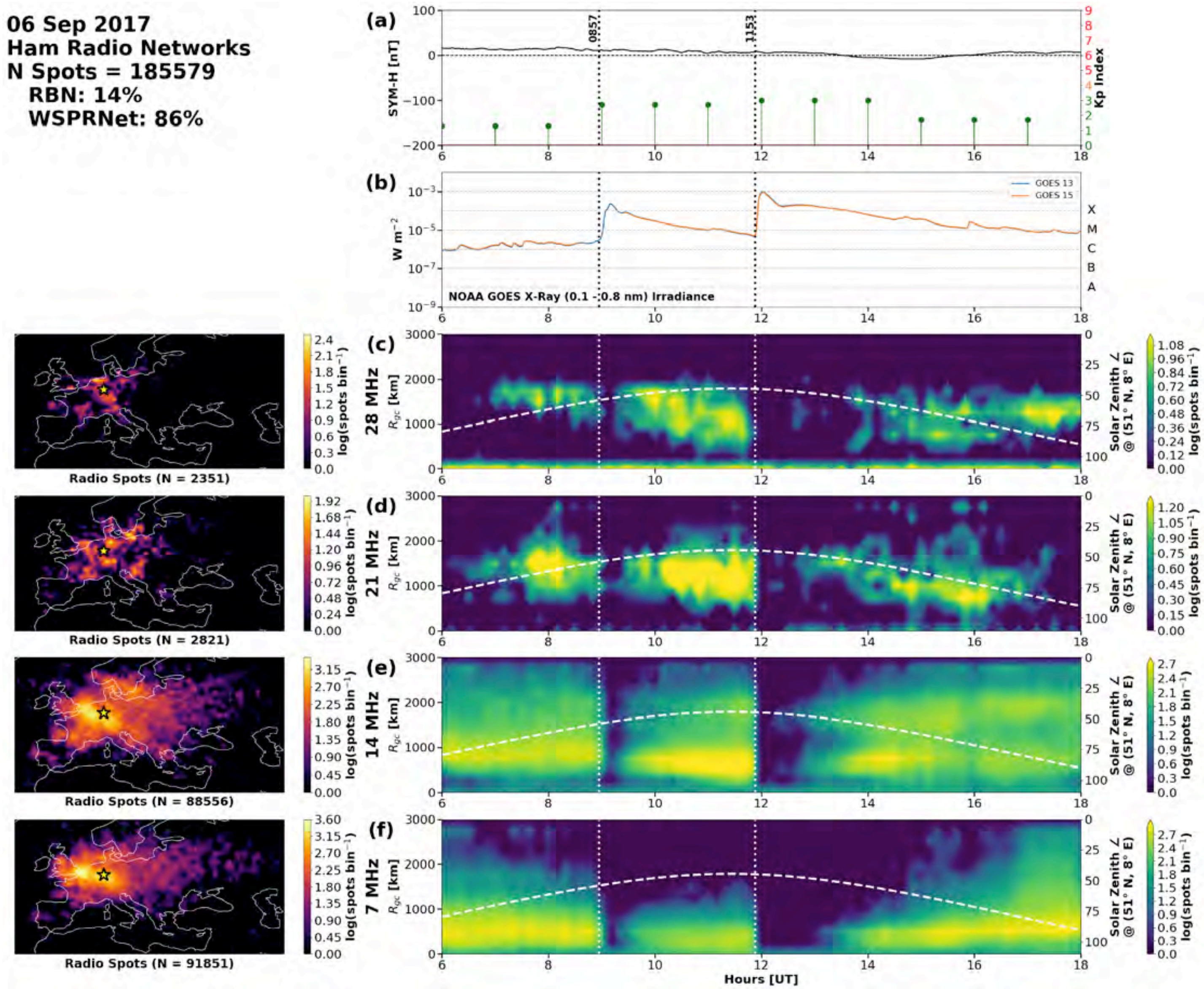
Solar Flare



6 September 2017



Solar Flare



06 Sep 2017
Ham Radio Networks
N Spots = 185579
RBN: 14%
WSPRNet: 86%
(a)
SYM-H [nT]
Kp Index
0857
1153
(b)
W m^{-2}
GOES 13
GOES 15
NOAA GOES X-Ray (0.1 - 0.8 nm) Irradiance
X
M
C
B
A
(c)
28 MHz
Radio Spots (N = 2351)
(d)
21 MHz
Radio Spots (N = 2821)
(e)
14 MHz
Radio Spots (N = 88556)
(f)
7 MHz
Radio Spots (N = 91851)
R_{gc} [km]
log(spots bin^{-1})
Solar Zenith ∠ @ (51° N, 8° E)
Hours [UT]

Riometer

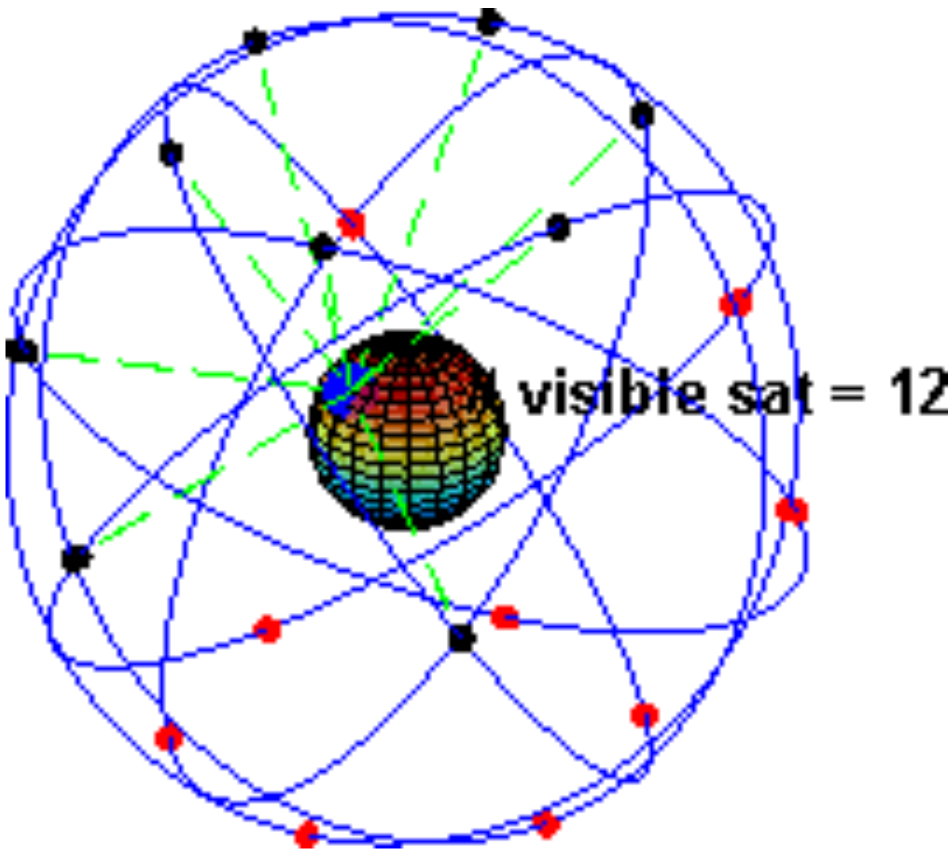
- **R**elative **I**onopheric **O**pacity **M**eter
- Directly measures absorption of cosmic rays
- Indirectly measures electron density, particle precipitation
- Typically passive instrument 30-50 MHz

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

Photo: Derek McKay

GNSS and the Ionosphere

GPS Navigation and Positioning System



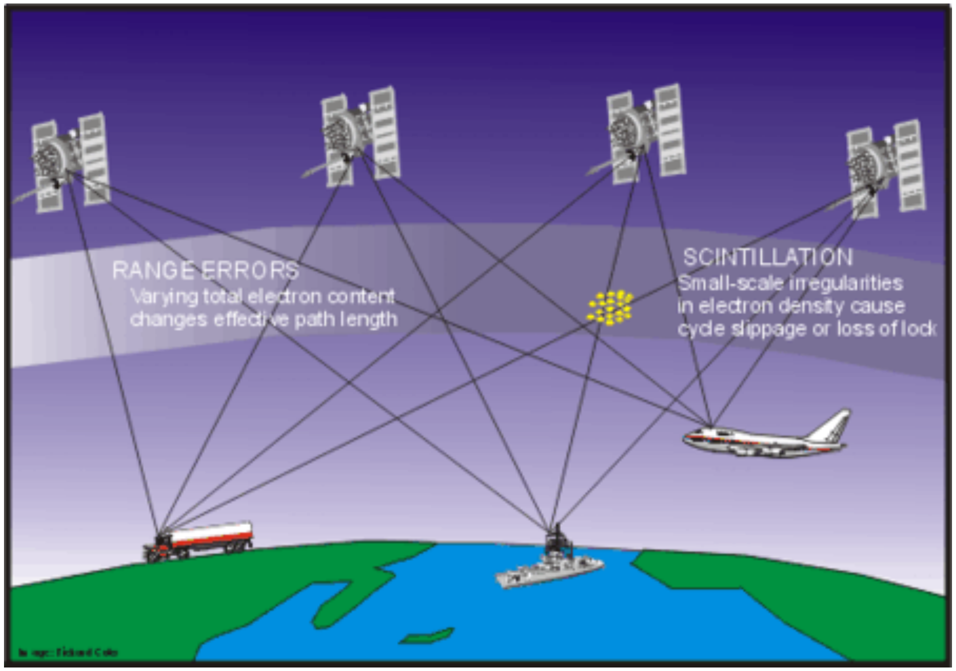
- Currently 29 satellites in orbit in 6 orbital planes
- Transmit coded signal at two frequencies: 1227 and 1575 MHz
- Need signals from 4 satellites to give time and fix location.

Operational and Planned Global Navigation Satellite Systems (GNSS)

System	GPS	GLONASS	BeiDou/ COMPASS	Galileo	NAVIC	QZSS
Owner	United States	Russia	China	EU	India	Japan
Coverage	Global	Global	Regional (Global by 2020)	Global	Regional	Regional
Orbital altitude	20,180 km	19,130 km	21,150 km	23,222 km	36,000 km	32,000 km
Total Number of satellites	**31** (at least 24 by design)	**28** (at least 24 by design)	5 geostationary orbit (GEO) 30 medium Earth orbit (MEO)	18 satellites in orbit, 30 operational satellites budgeted	3 geostationary orbit (GEO) 5 geosynchronous (GSO) medium Earth orbit	4 in elliptical inclined geosynchronous orbits
Frequencies	1.57542 GHz (L1 signal) 1.2276 GHz (L2 signal)	Around 1.602 GHz Around 1.246 GHz	1.561098 GHz 1.589742 GHz 1.20714 GHz 1.26852 GHz	1.164-1.215 GHz 1.260–1.300 GHz 1.559–1.592 GHz	1.1765 GHz 2.4920 GHz	
Status	Operational	Operational	22 satellites operational, 40 additional satellites 2016-2020	18 satellites operational 12 additional satellites 2017-2020	6 satellites fully operational, IRNSS-1A partially operational	4 satellites system Operational in 2018

Ionospheric Effects on GPS

- **TEC**
  - Induces Range Errors
  - Highly variable with location, time, season, magnetic and solar activity
- **Scintillation**
  - Induces rapid changes in amplitude and phase of incoming signal
  - Can induce cycle slips and loss of lock that degrade performance



- **Masking**
  - Naturally generated solar radio waves overpowers GPS signal so it can't be received

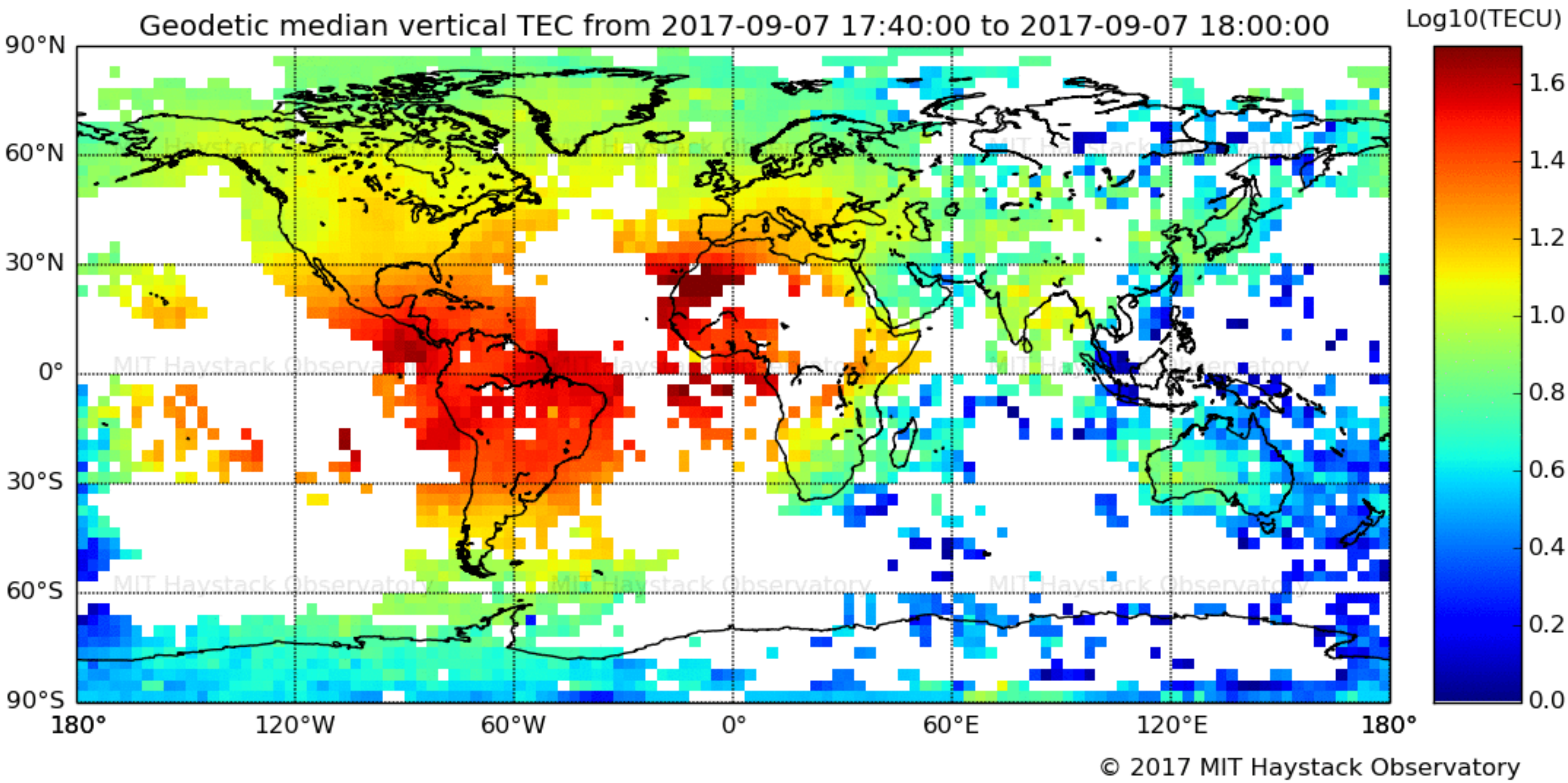
Total Electron Content (TEC)

- Group delay in radio signal is proportional to the integral of electron density along the wave path.

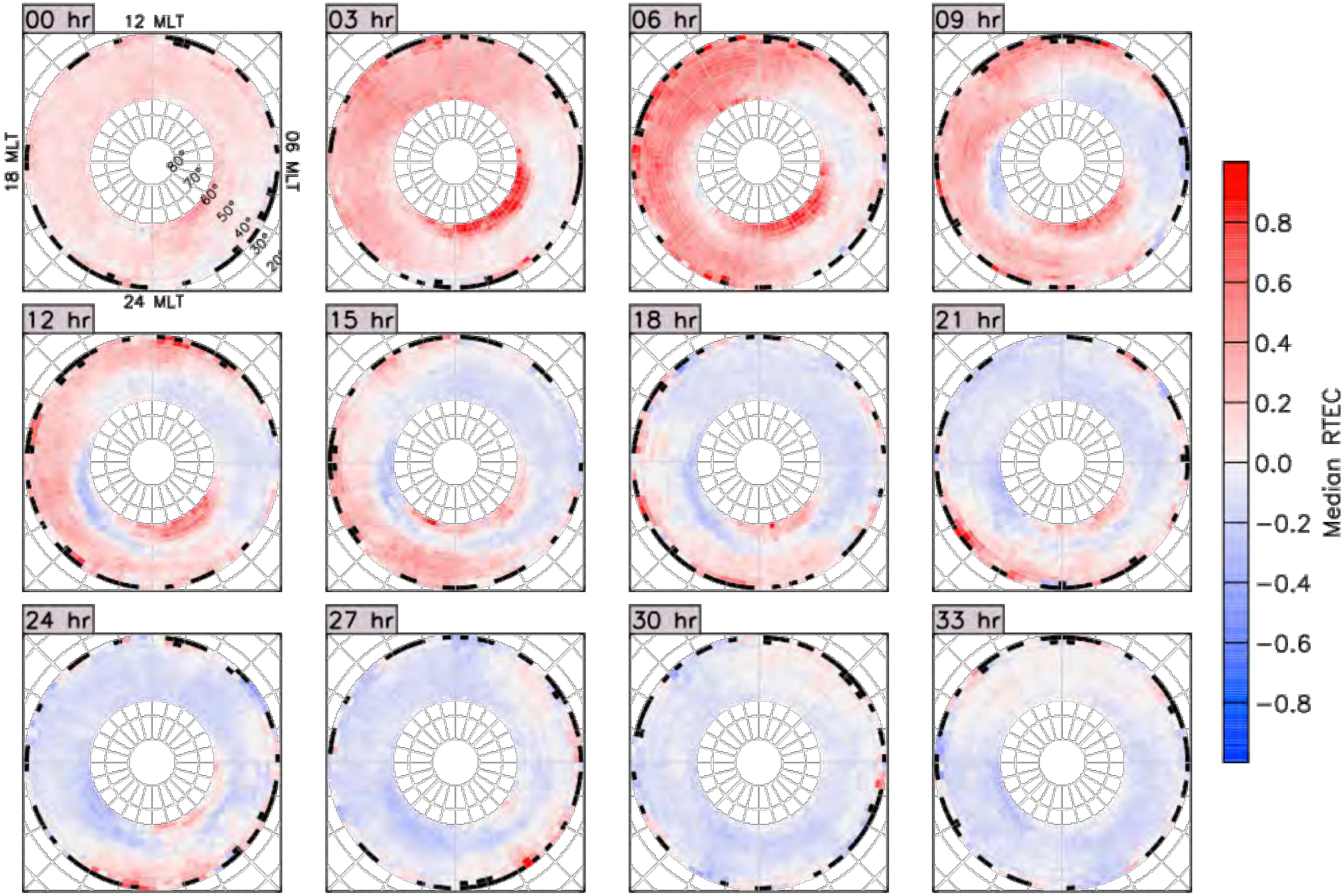
- With signals at two frequencies, difference in arrival time can be used to calculate TEC and hence remove effect.

- Sharp spatial gradients in TEC, such as are generated during geomagnetic storms can cause significant errors.

Global TEC Maps

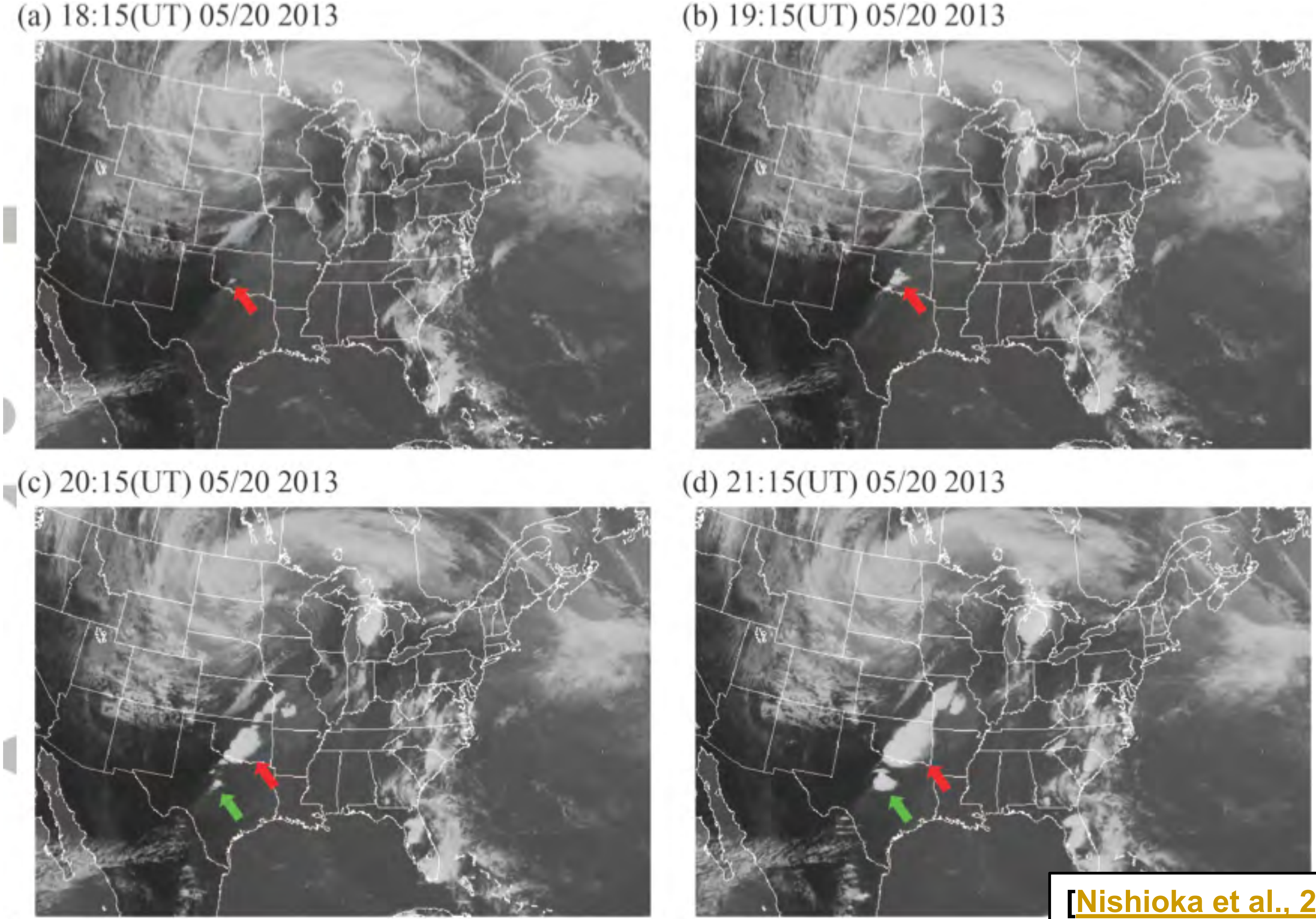


Ionospheric Storm Response



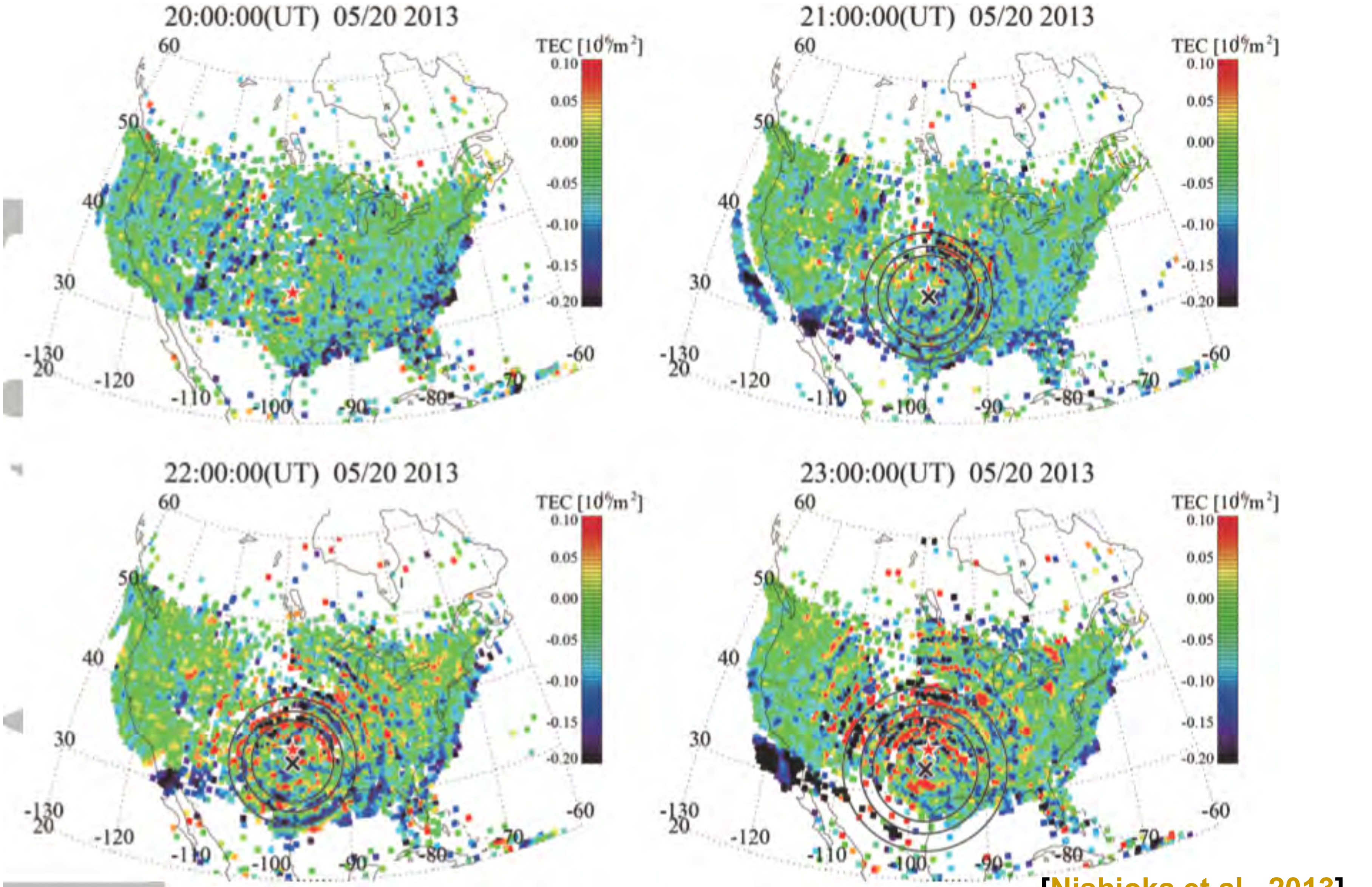
[Thomas et al., 2016]

Development of Tornado Cell



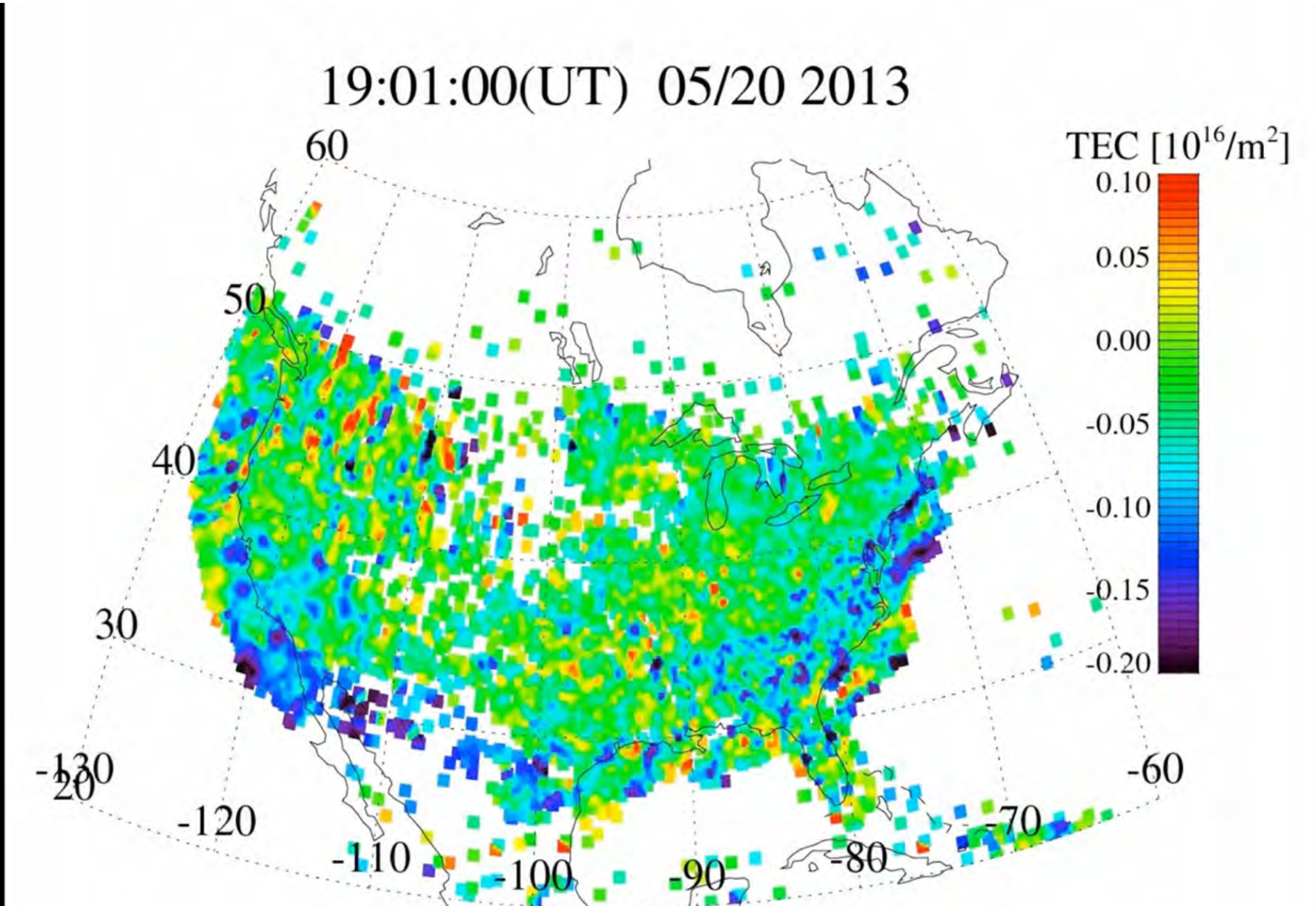
[Nishioka et al., 2013]

MSTID Resulting from Tornado



[Nishioka et al., 2013]

MSTID Resulting from Tornado



[Nishioka et al., 2013]

Ionospheric Scintillation

- Caused by ionospheric turbulence (e.g. equatorial spread F) creating density structures with a length scale comparable with the signal wavelength

- This causes the waves to diffract and scatter causing interference

- At receiver both wave amplitude and phase vary on short time scale leading to signal loss

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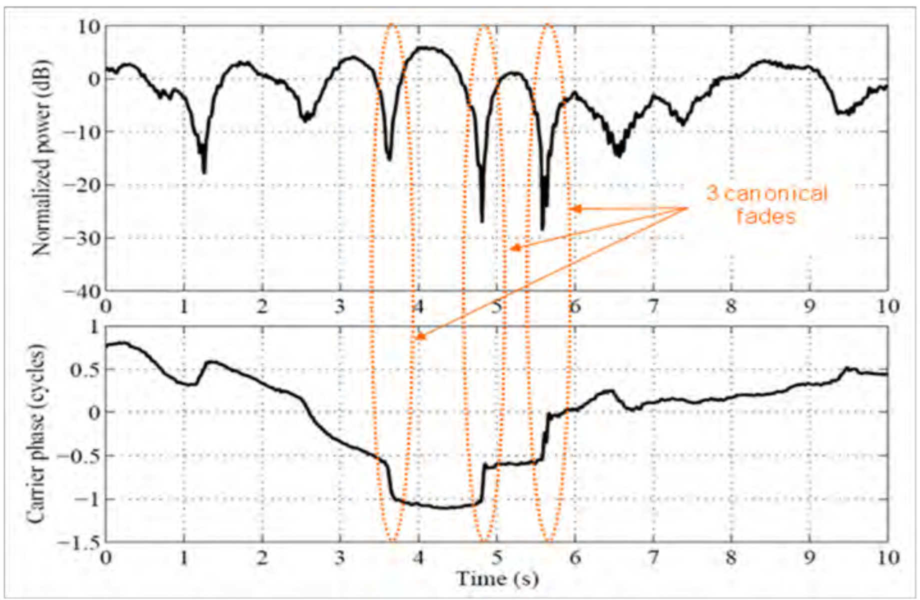
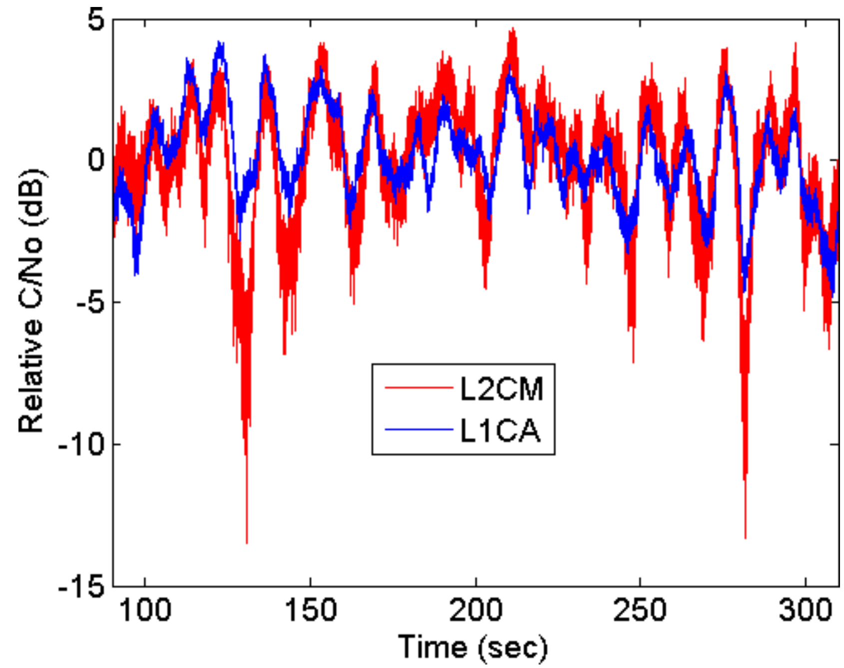
Ionospheric Scintillation

Ionospheric scintillation affects both signal amplitude and phase.

- Amplitude and phase scintillation are not independent



- L1 and L2 frequency fades are not independent
- L2 frequency fades are larger



Incoherent Scatter Radar (ISR)

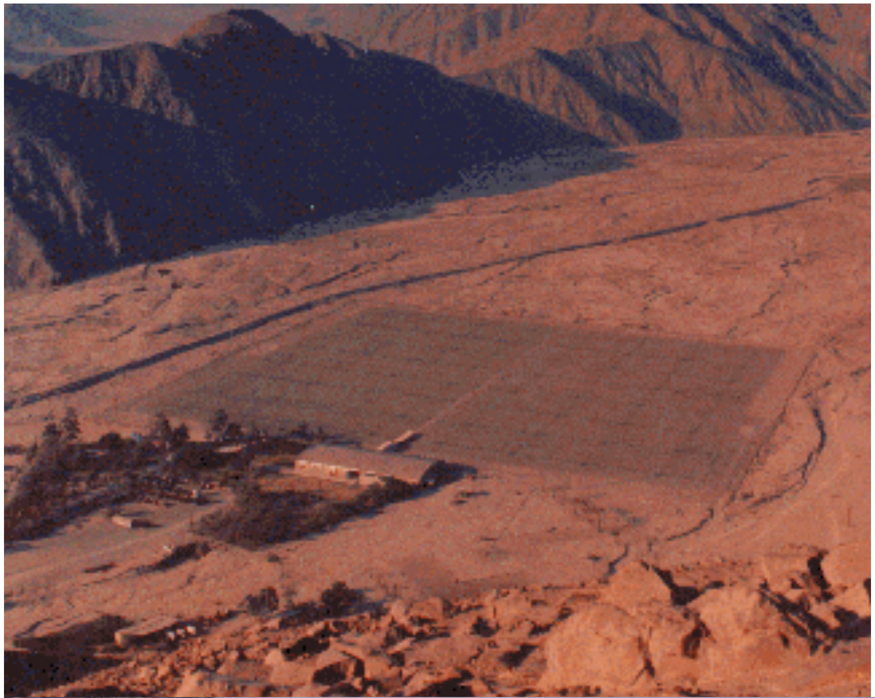
Incoherent Scatter Radars

Arecibo ISR

- Located in Puerto Rico
- Operating since 1963
- Initiated by William E. Gordon
  - Pioneer of ISR
  - Born Patterson, NJ
  - Undergrad Montclair State
- Largest radar dish (305 m)
- 440 MHz, 1-2 MW

Jicamarca ISR

- Located in Peru
- Operating since 1961
- Phased array of 18,432 dipole elements covering 85,000 m^2
- Located in the dessert, very good signal-to-noise measurements
- 49.9 MHz, 3*1.5 MW



Millstone Hill ISR

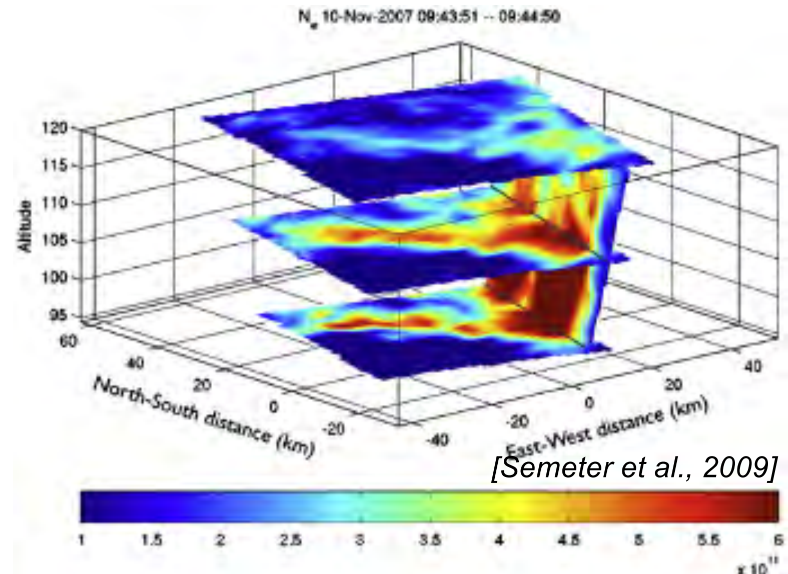
- Located near Westford (outside Boston, MA)
- Operating since 1974
- One vertical 67 m dish, one fully-steerable 46 m dish
- 440 MHz, 2.5 MW

EISCAT Svalbard Radar (ESR)

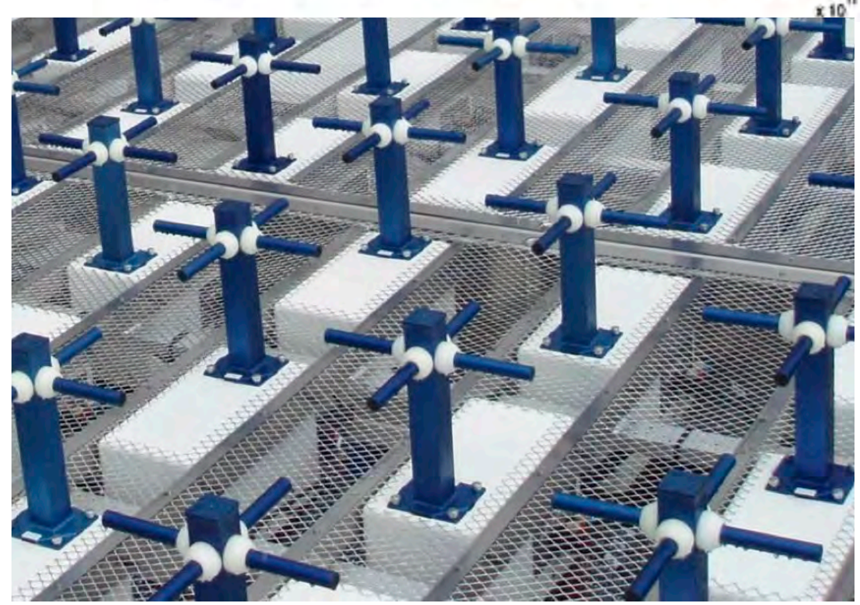
- Located here in Longyearbyen, Svalbard
- One fully steerable 32 m antenna (since 1996), one fixed 42 m antenna (since 2000)
- 500 MHz, 1 MW

Poker Flat ISR (PHISR)

- AMISR Phased Array (30×30m)
- Poker Flat, Alaska
- 450 MHz, 1.3 MW
- Operational since 2007



[Semeter et al., 2009]

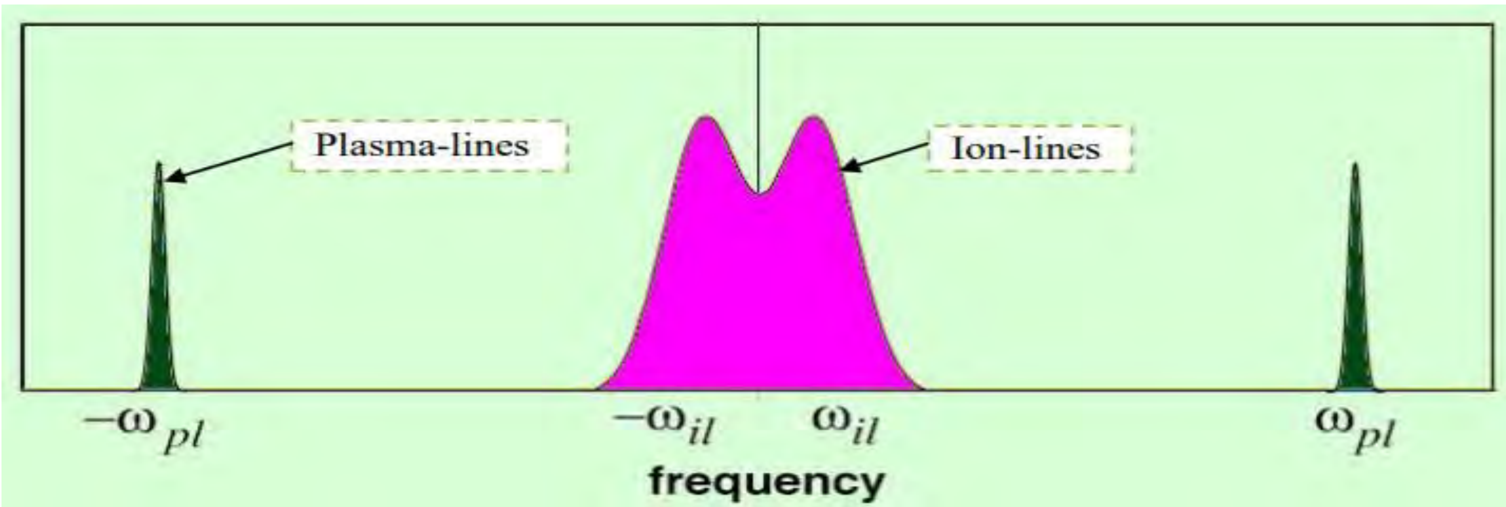


ISR Power Spectrum

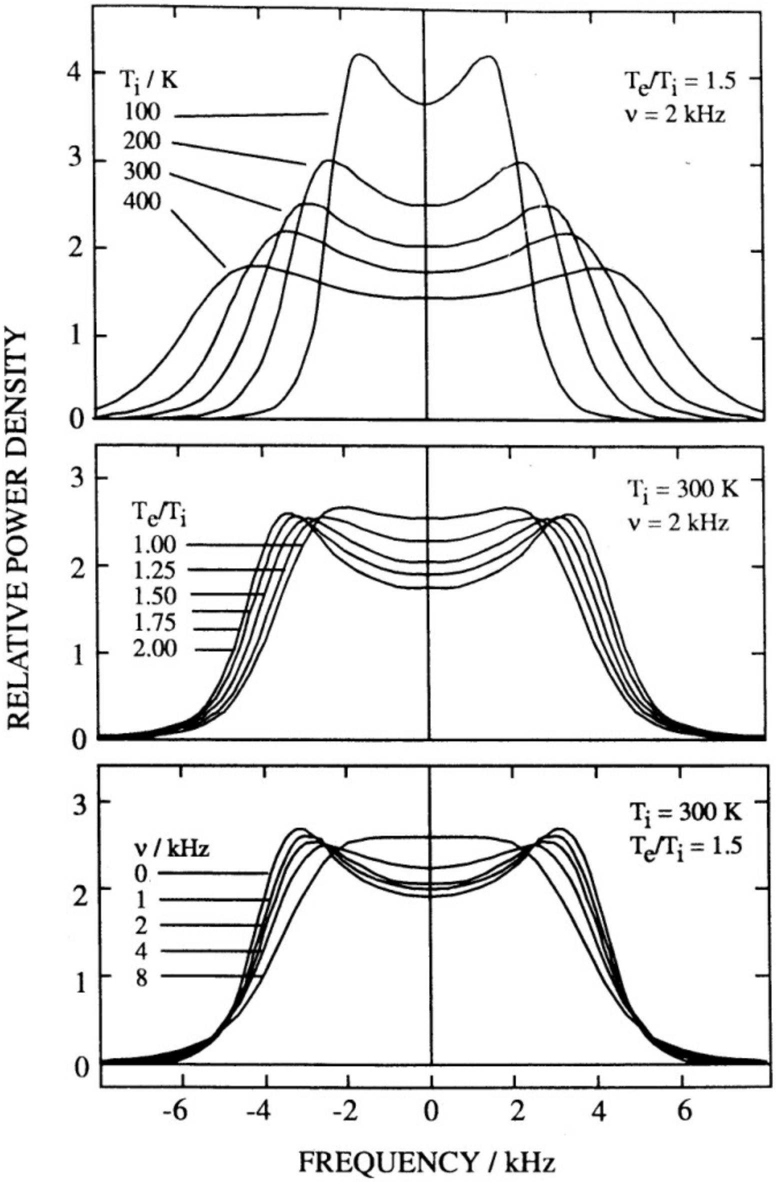
ISRs detect scatter from single electrons by Thompson Scattering (scattering of EM radiation by a free particle)

- The radar transmits a radio wave
- This hits the ionospheric free electrons, which are in random thermal motion
- The radio wave causes the electrons to oscillate
- They then emit their own radio waves in all directions
- Only a small fraction of the energy returns back to the radar

P_t = 1 MW, P_r – 10^{-18} W

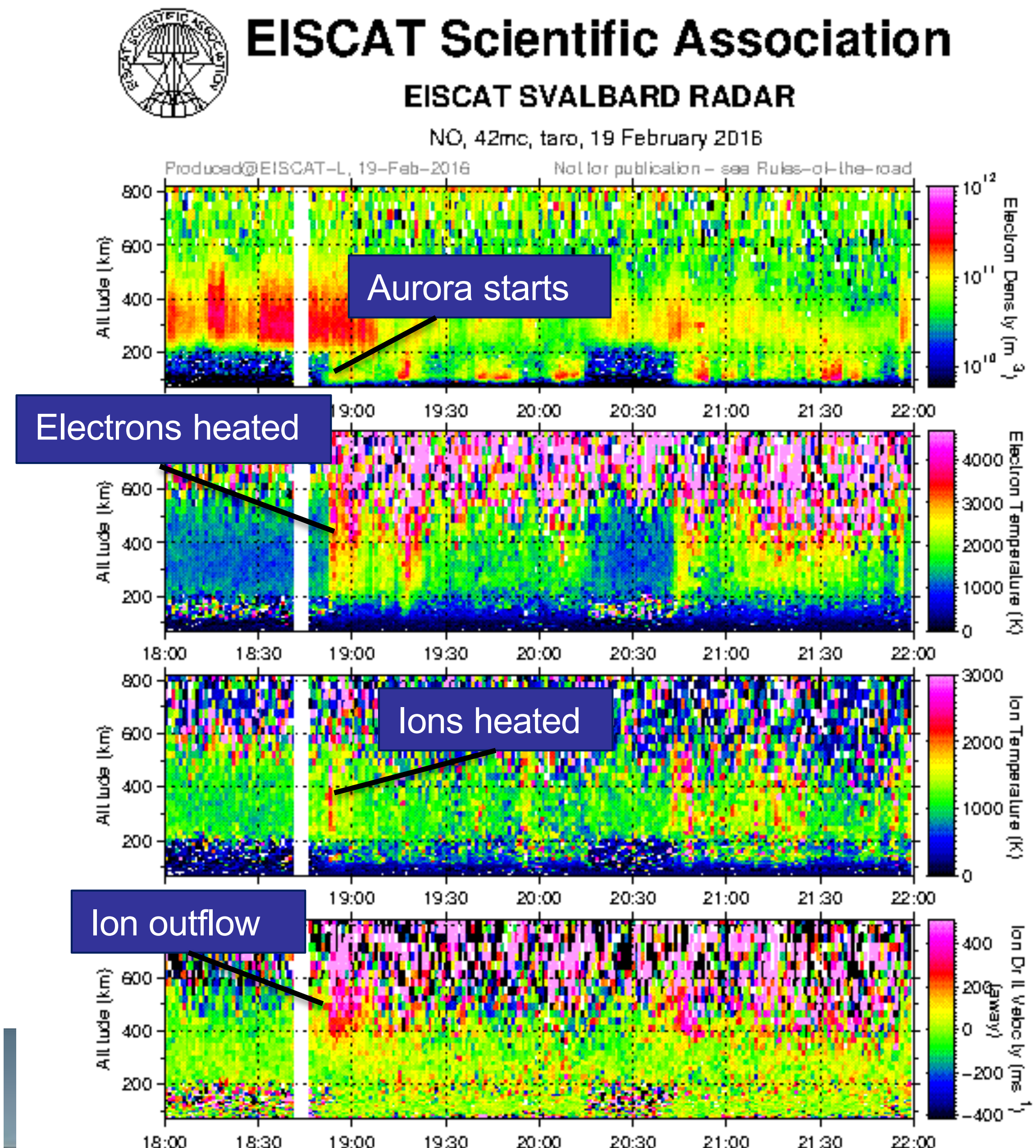


Ion acoustic power spectrum



- Fit data to model to extract 6 key ionospheric parameters:
  - Electron number density (n_e)
  - Electron temperature, T_e
  - Ion temperature, T_i
  - Ion composition,
  - Ion velocity, v
  - Ion-neutral collision frequency, ν_{in}
- And estimates of the errors in these parameters

Data: Auroral Substorm (Nightside)

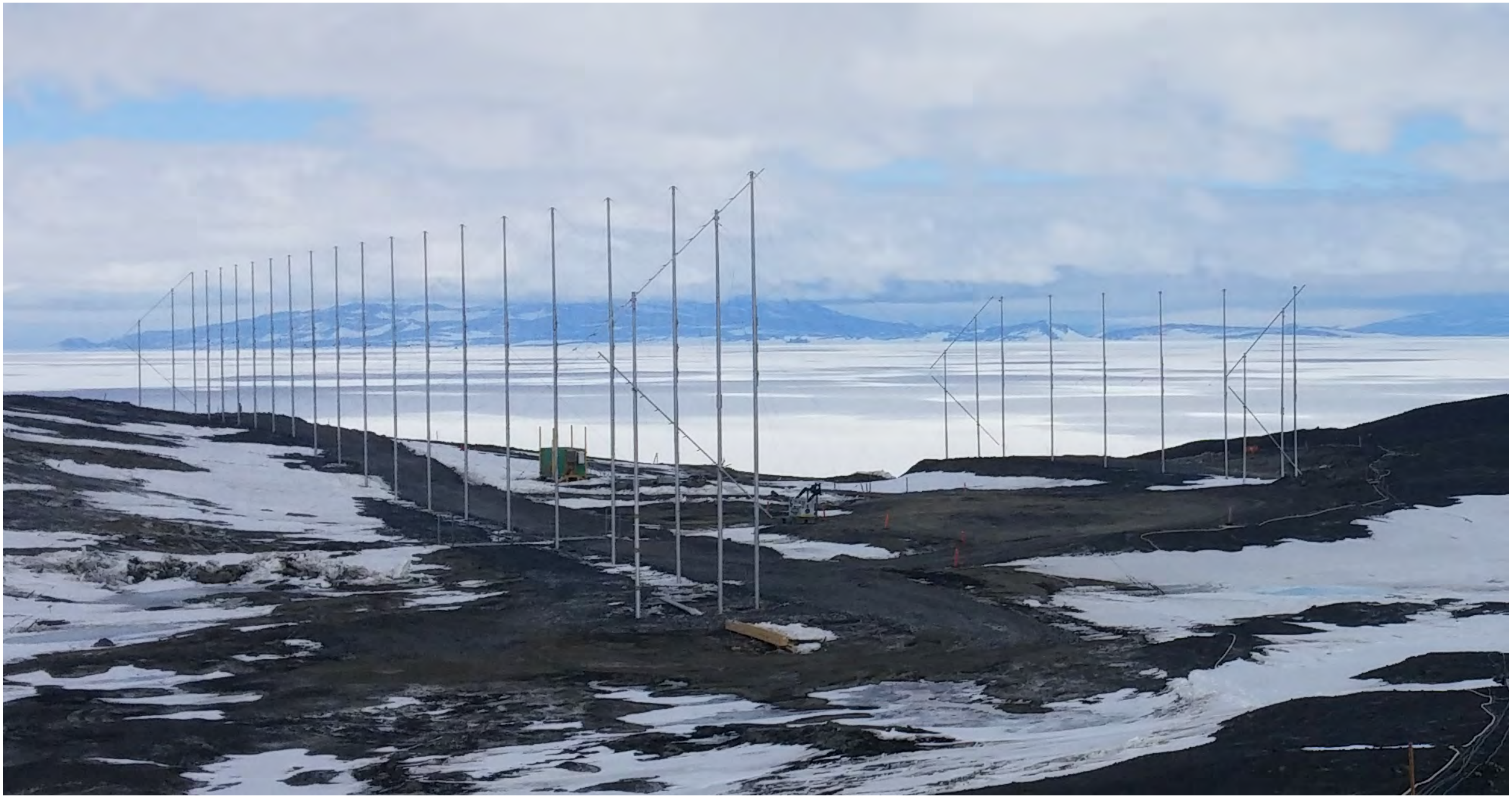


- We can see signatures of aurora. The incoming energetic auroral particles collide with the atmospheric particles
- There is more ionization and heating due to these collisions
- Ions also flow outwards into space

SuperDARN

COHERENT SCATTER RADAR

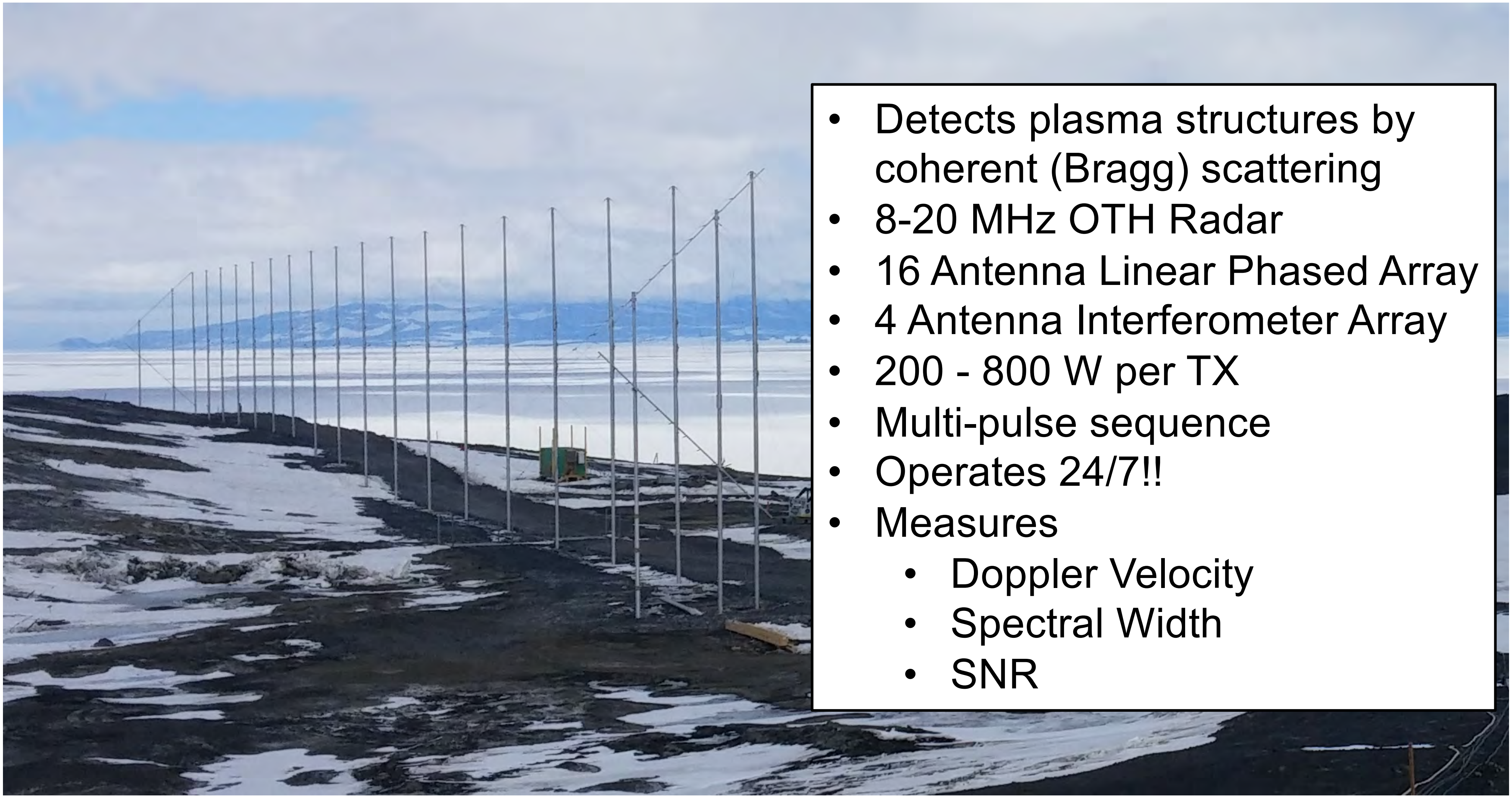
Super Dual Auroral Radar Network



SuperDARN Radar, McMurdo Station Antarctica

Photo N. Frissell, 2014

Super Dual Auroral Radar Network

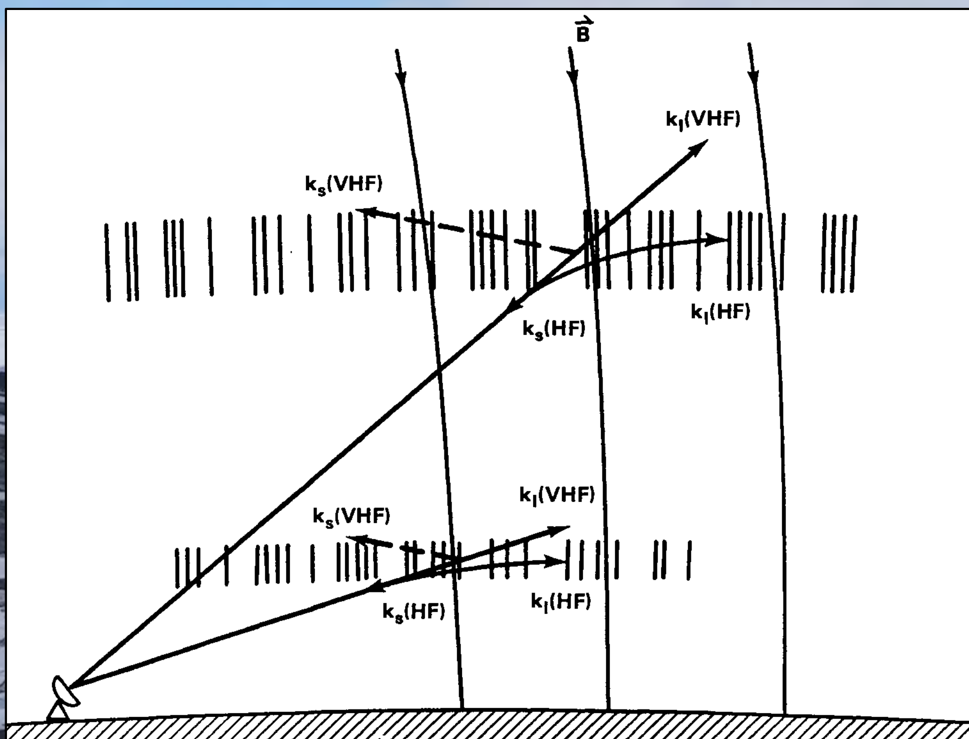


- Detects plasma structures by coherent (Bragg) scattering
- 8-20 MHz OTH Radar
- 16 Antenna Linear Phased Array
- 4 Antenna Interferometer Array
- 200 - 800 W per TX
- Multi-pulse sequence
- Operates 24/7!!
- Measures
  - Doppler Velocity
  - Spectral Width
  - SNR

SuperDARN Radar, McMurdo Station Antarctica

Photo N. Frissell, 2014

Super Dual Auroral Radar Network



[Greenwald et al., 1995]

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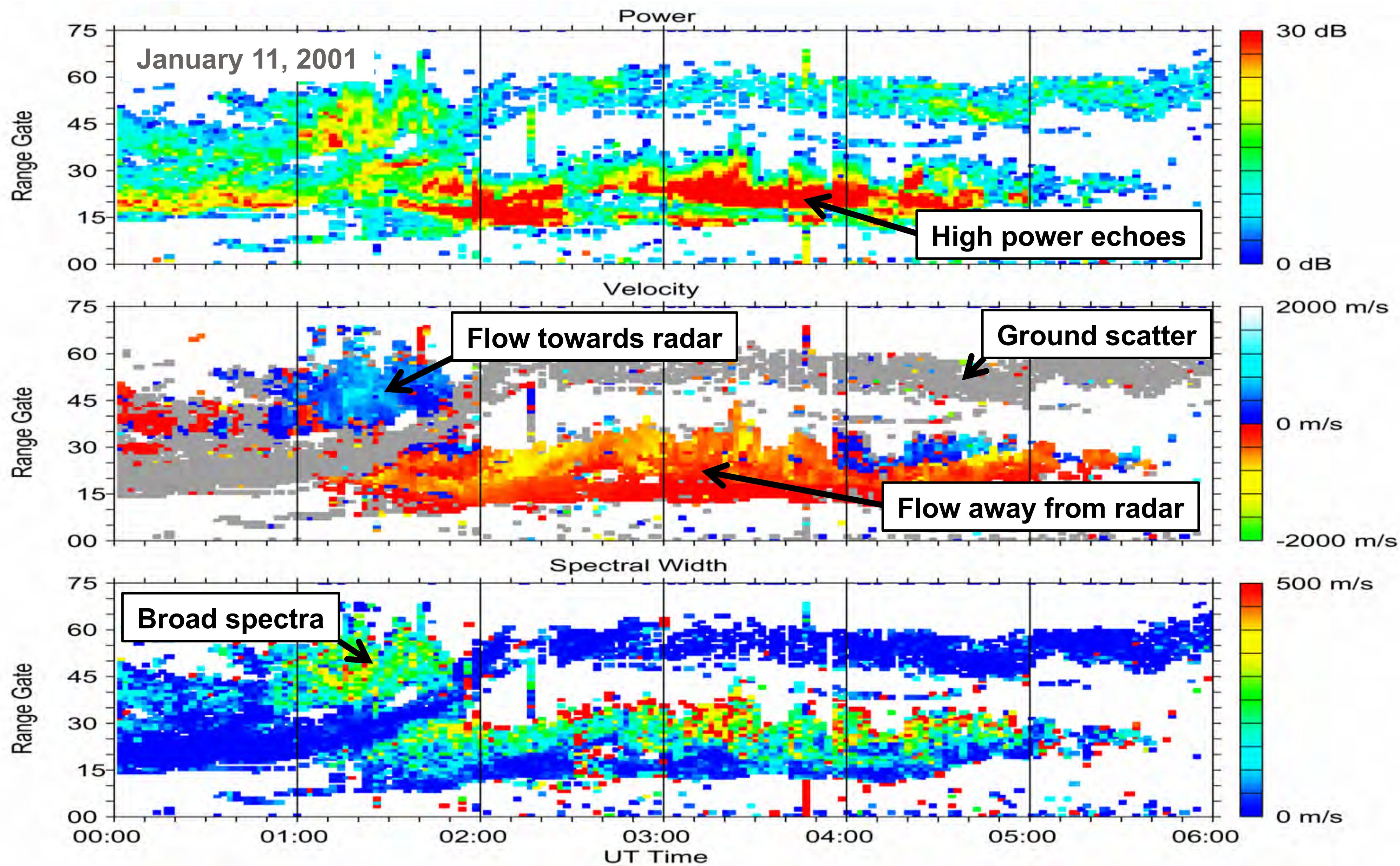
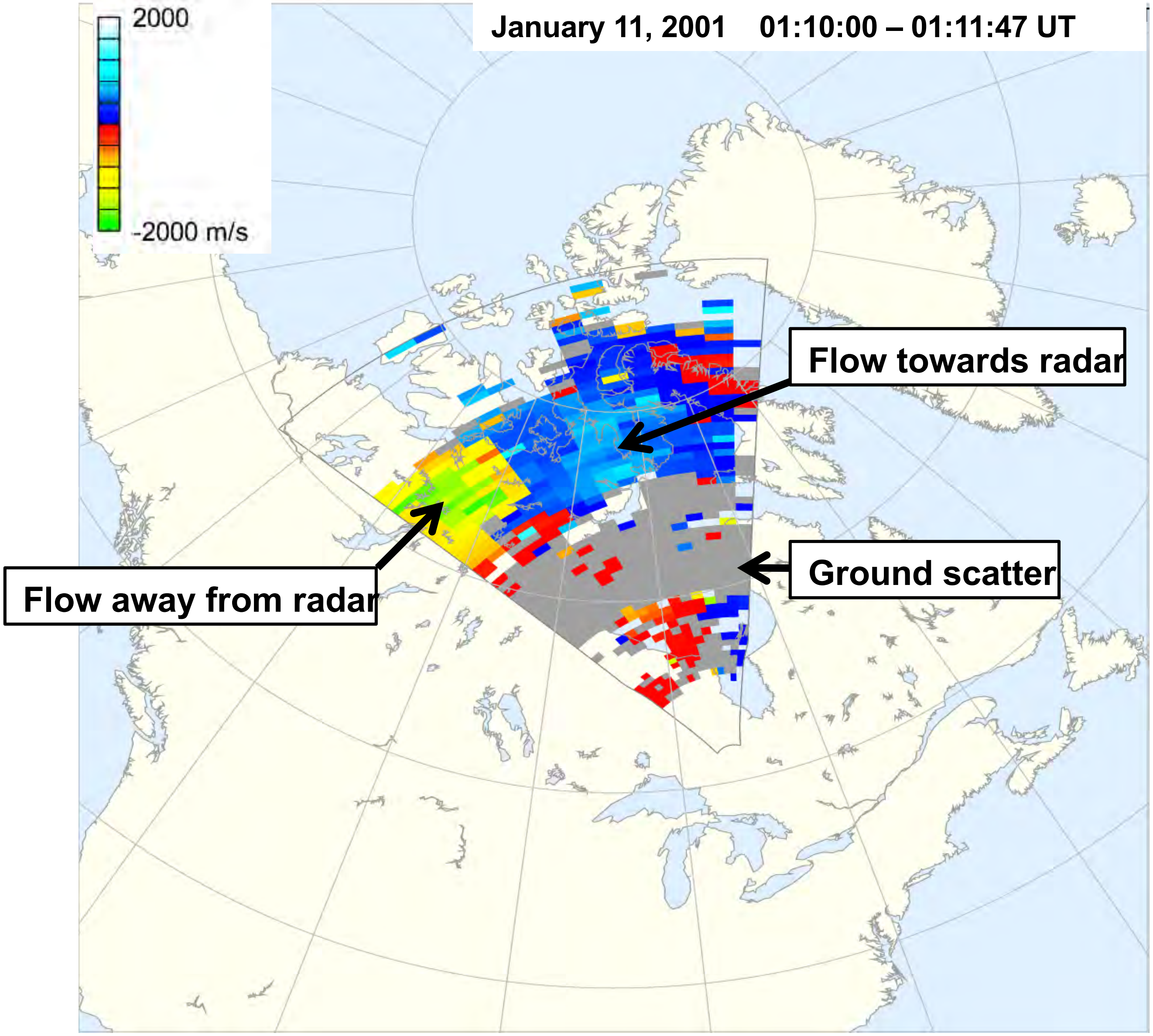
SuperDARN Radar, McMurdo Station Antarctica

Photo N. Frissell, 2014

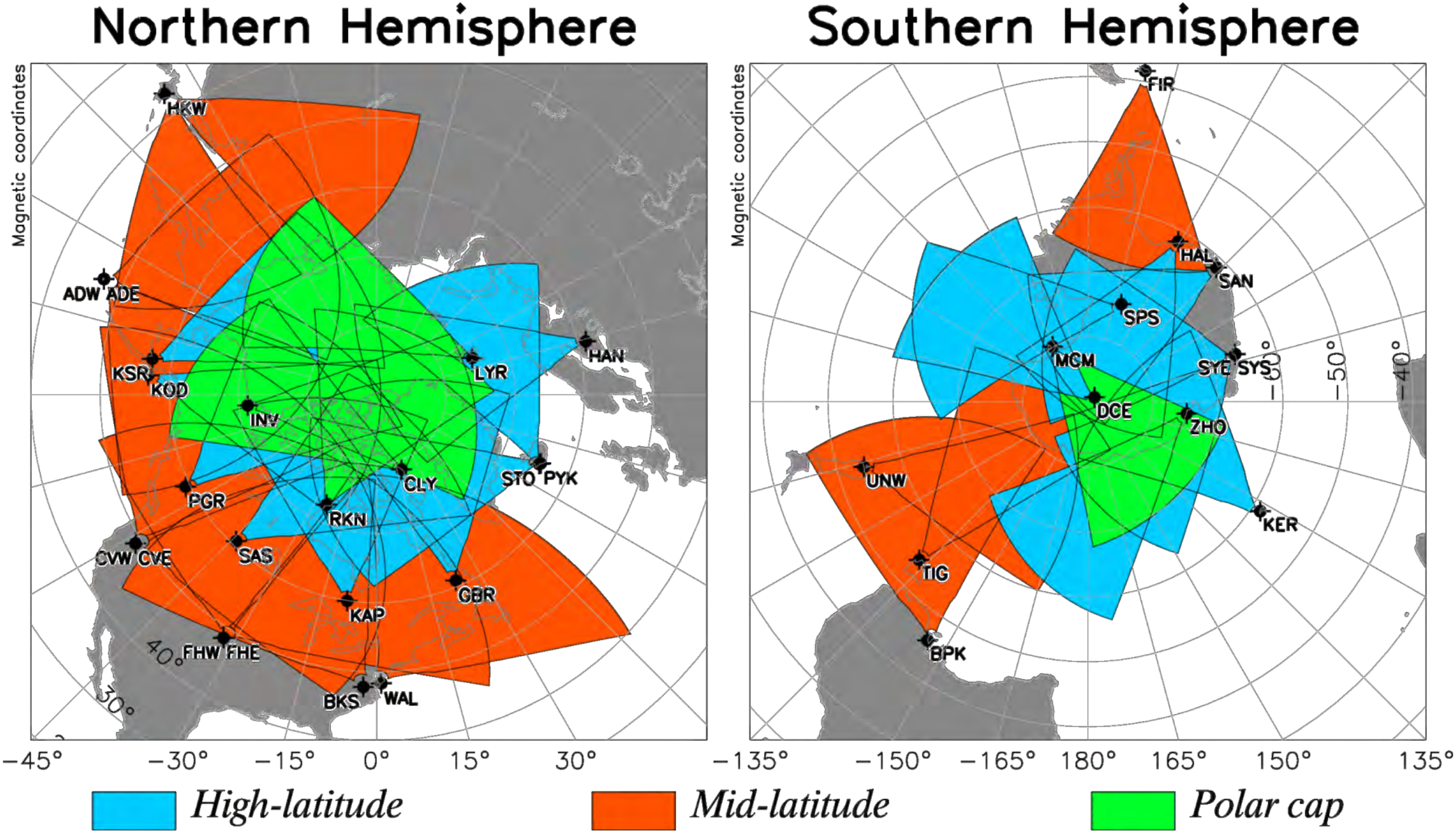
Range-Time Plot – Beam 4 Kapuskasing



Doppler Velocity Map – Kapuskasing

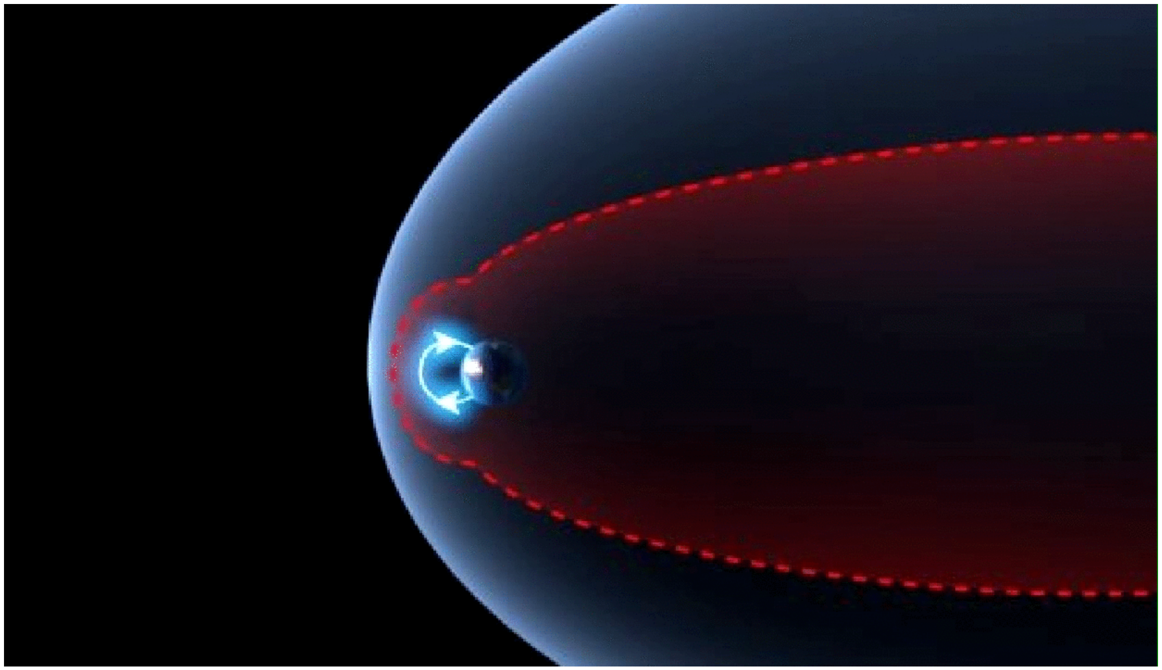


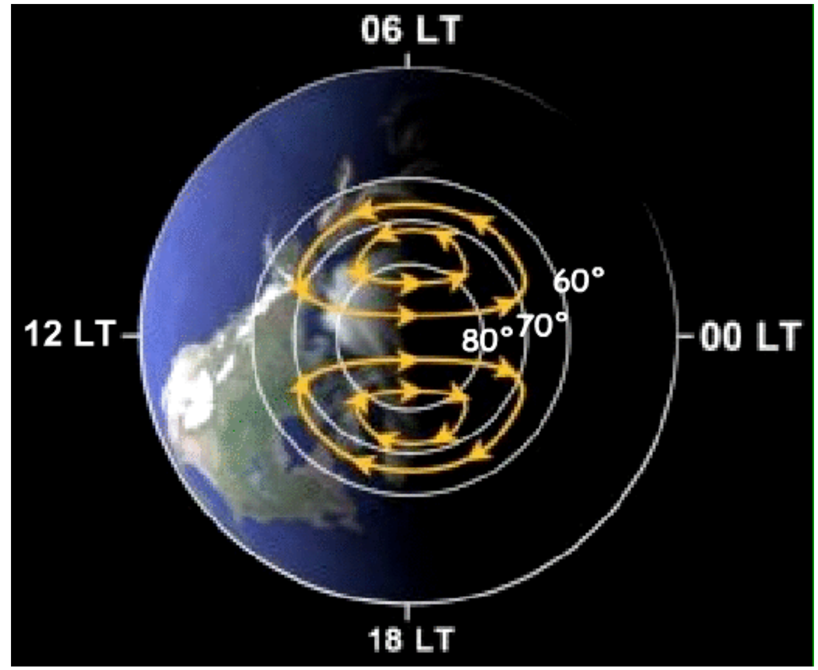
Super Dual Auroral Radar Network



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

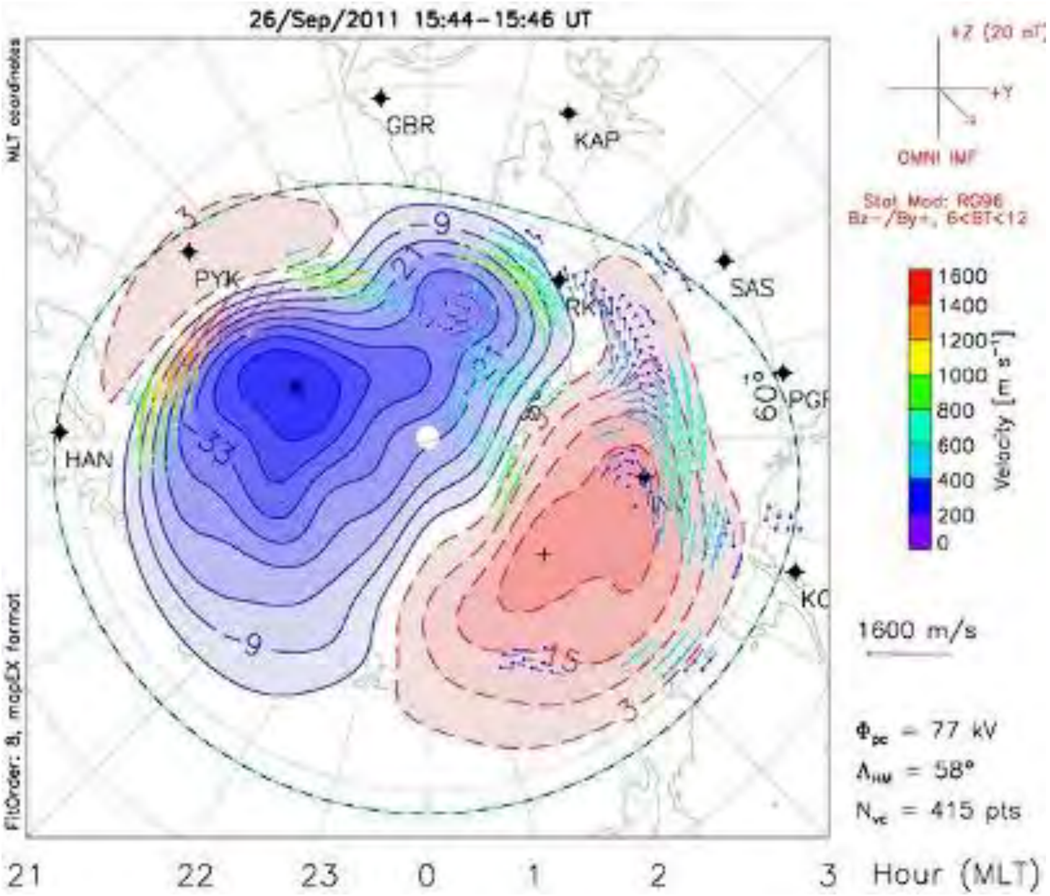
Magnetospheric Convection





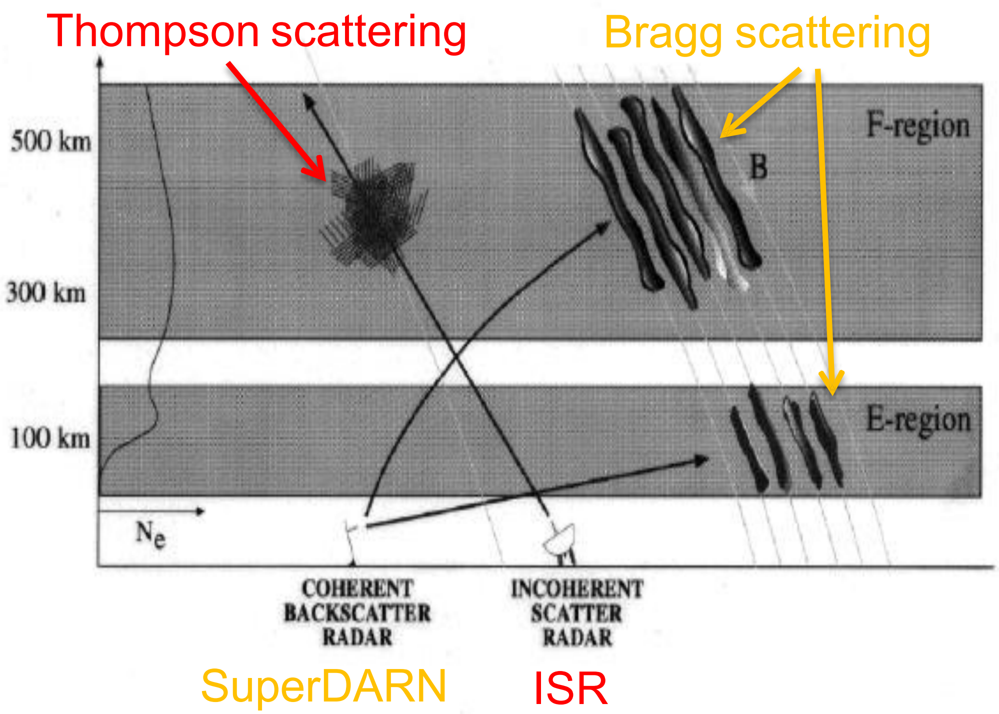
Super Dual Auroral Radar Network

SuperDARN
Global Ionospheric Convection Maps



- Data is taken from all the radars and fitted to a model
- From this we can build a map of how the plasma is moving over large areas
- Helps us to get a global picture of plasma circulation

EISCAT vs SuperDARN

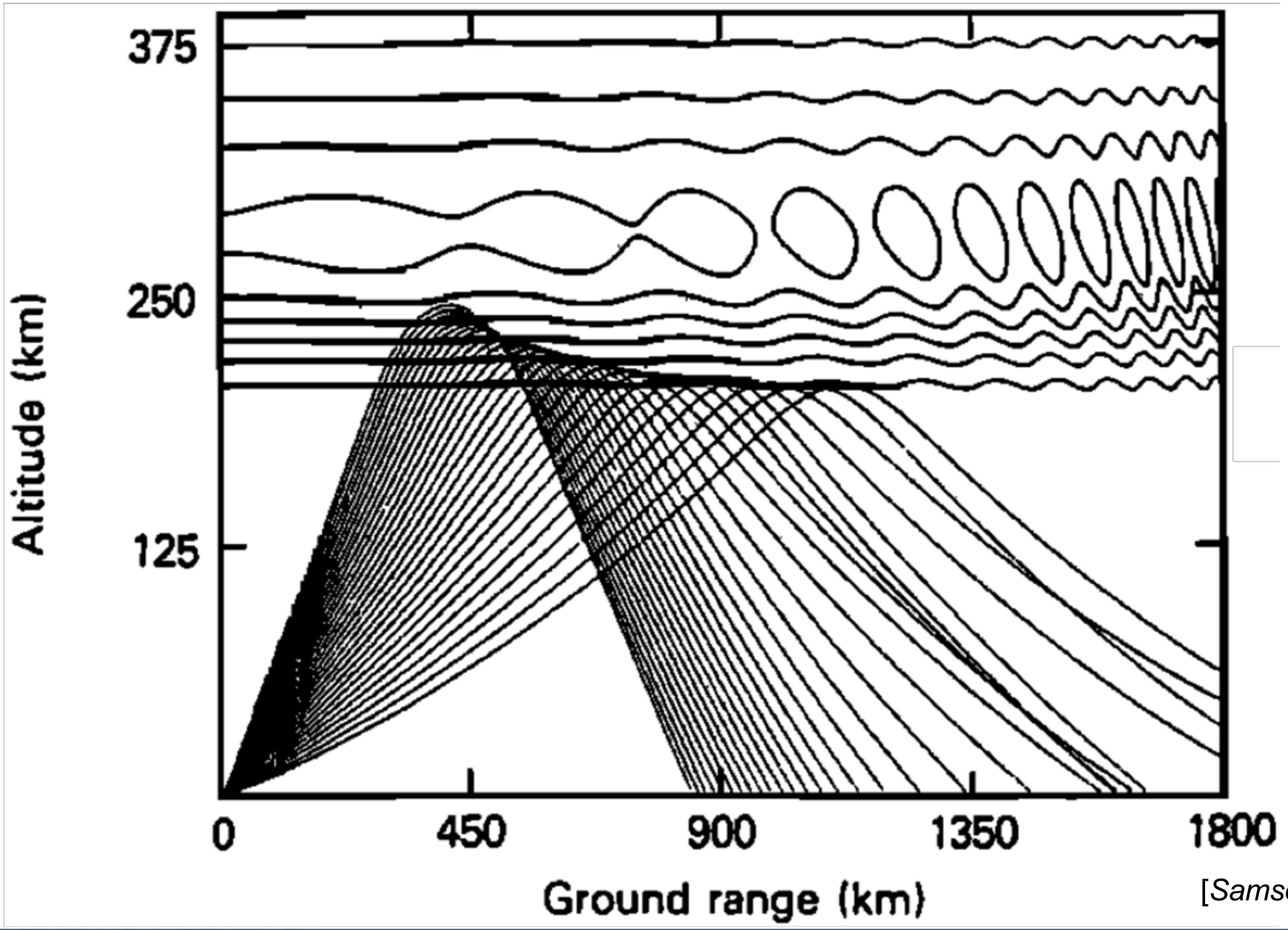


Radar	ISR	SuperDARN
Scatter type	Incoherent (Thompson)	Coherent (Bragg)
Frequency	Fixed (500 MHz)	Variable (9-20 MHz)
Range resolution	~100m-10km	15-45 km
Field of view	Narrow	Wide

- ISRs see smaller structures in any direction using Thompson scattering
- CSRs see bigger structures aligned with the magnetic field using Bragg scattering

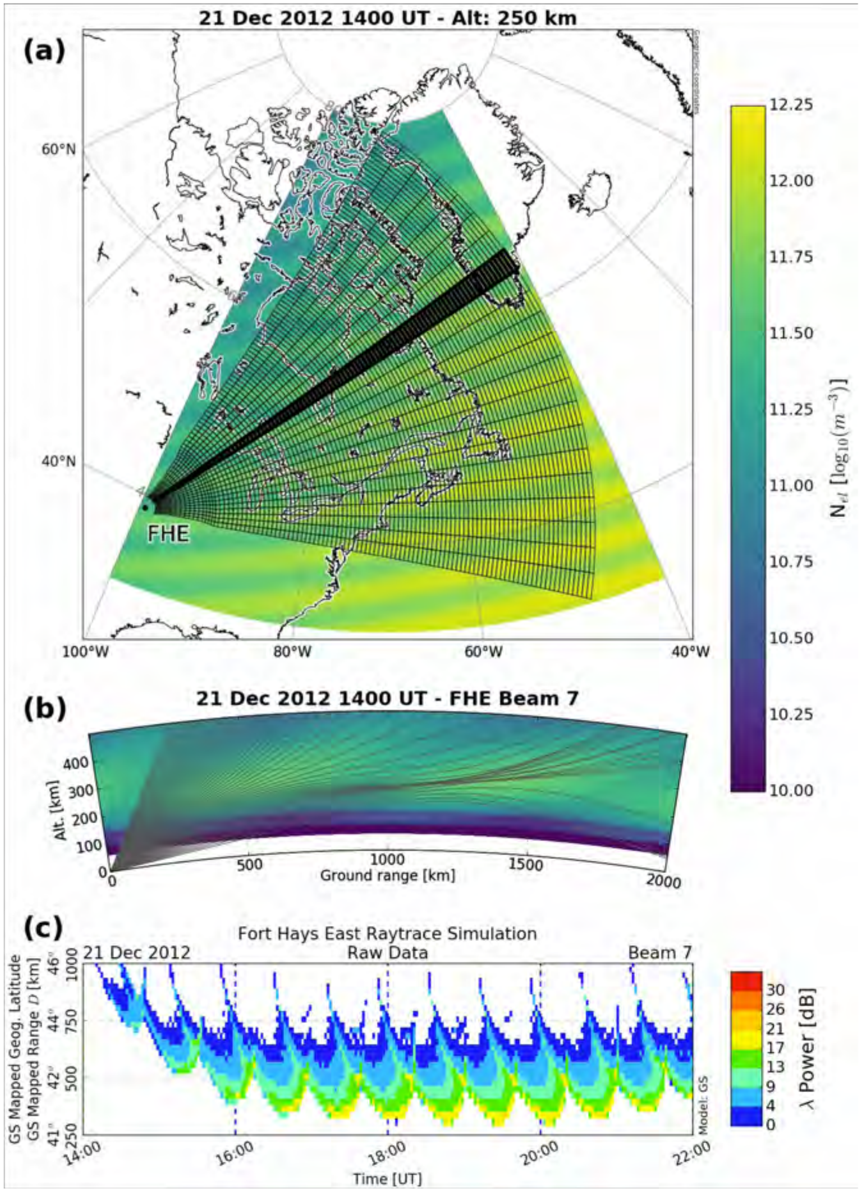
Medium Scale Traveling Ionospheric Disturbances

Now we are interested in the ground scatter…



[*Samson et al.*, 1990]

Medium Scale Traveling Ionospheric Disturbances



Ray trace simulation illustrating how SuperDARN HF radars observe MSTIDs.

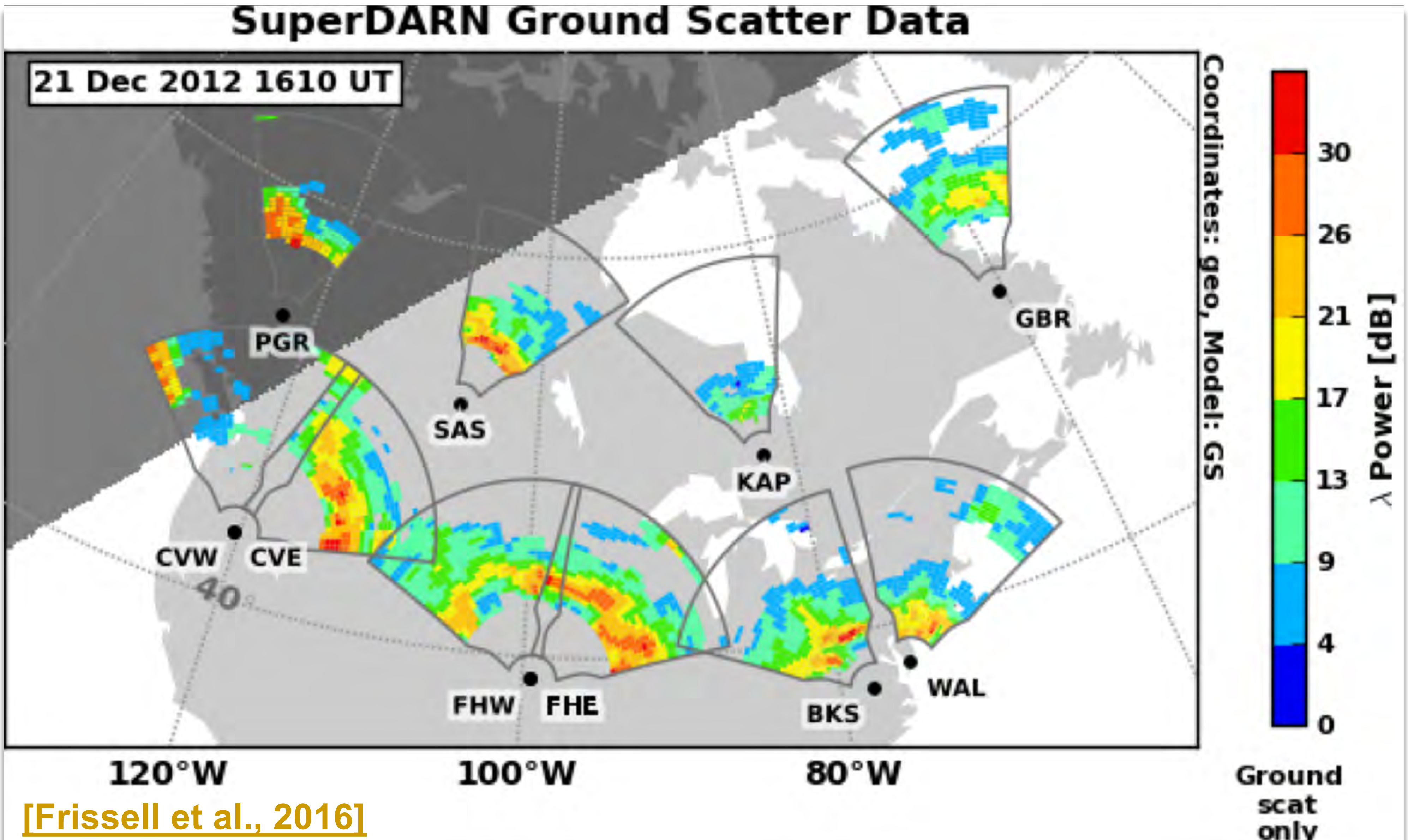
(a) Fort Hays East (FHE) radar field of view superimposed on a 250 km altitude cut of a perturbed IRI. FHE Beam 7 is outlined in bold.

(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]

SuperDARN MSTID Study



[Frissell et al., 2016]

MSTIDs Caused by Aurora?

Svalbard, 2010, N. Frissell

HamSCI
http://hamsci.org

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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?

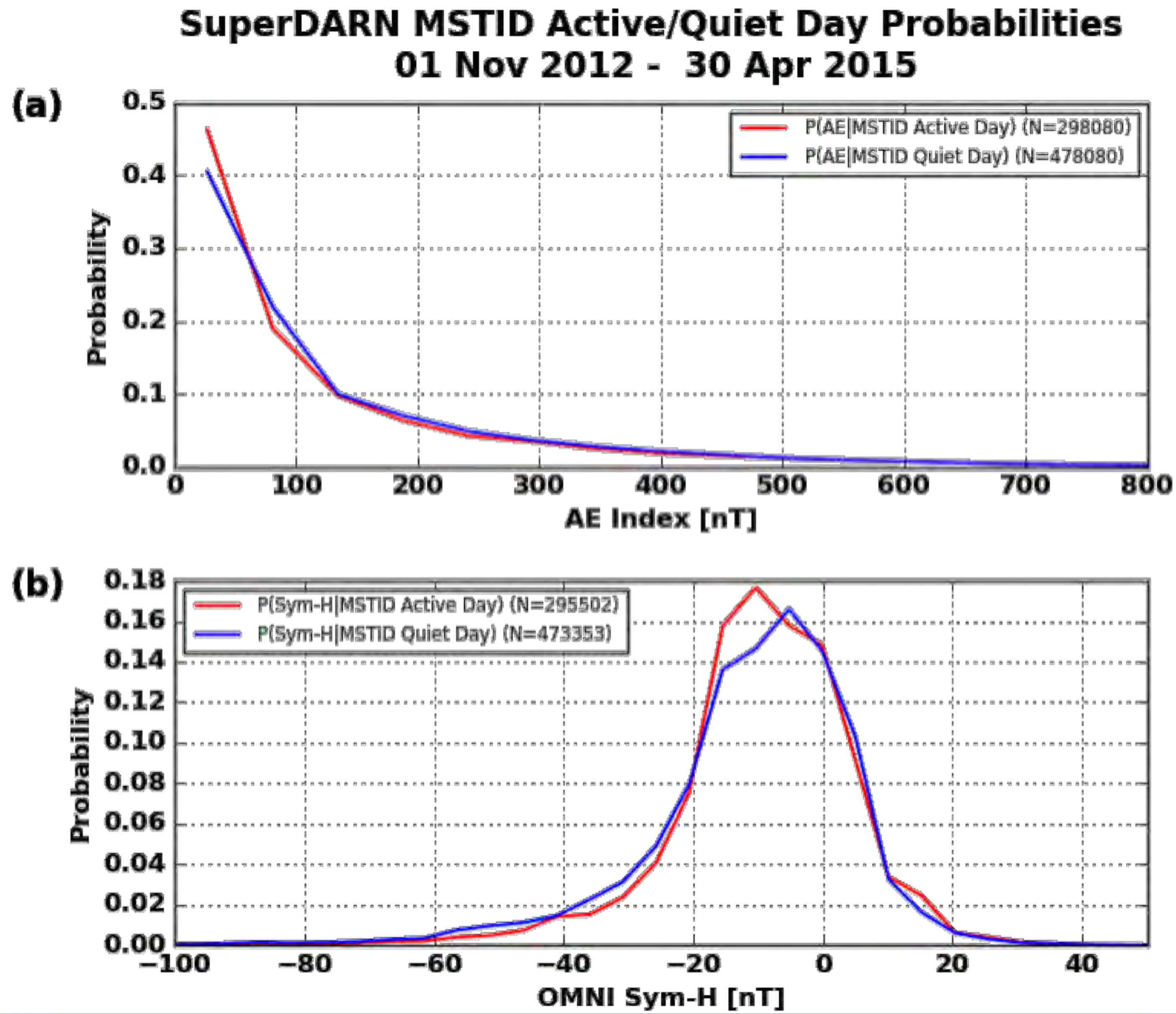
[*Samson et al.*, 1989, 1990; *Bristow et al.*, 1994, 1996; *Grocott et al.*, 2013; *Frissell et al.*, 2014]

Is it the Aurora?

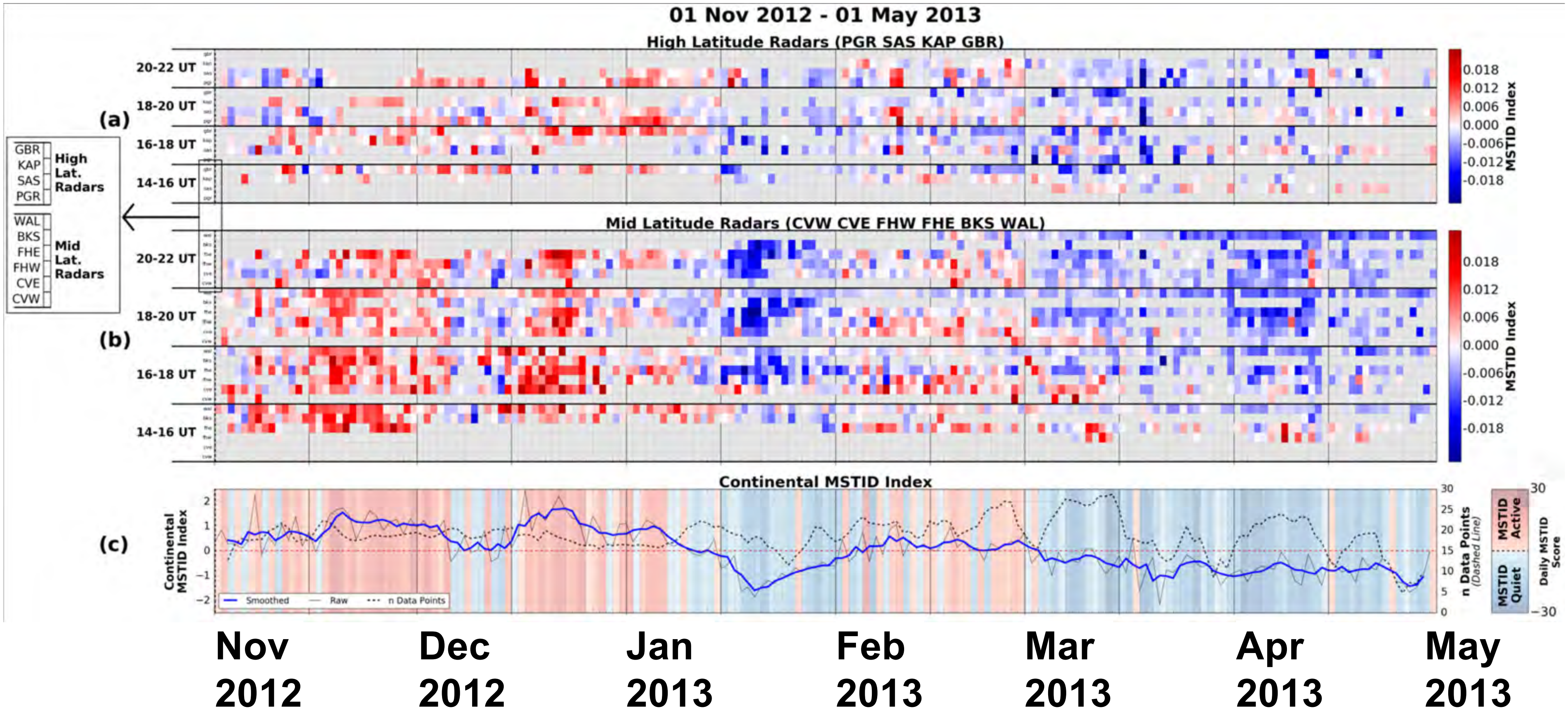
MSTID Active
MSTID Quiet

AE

SYM-H

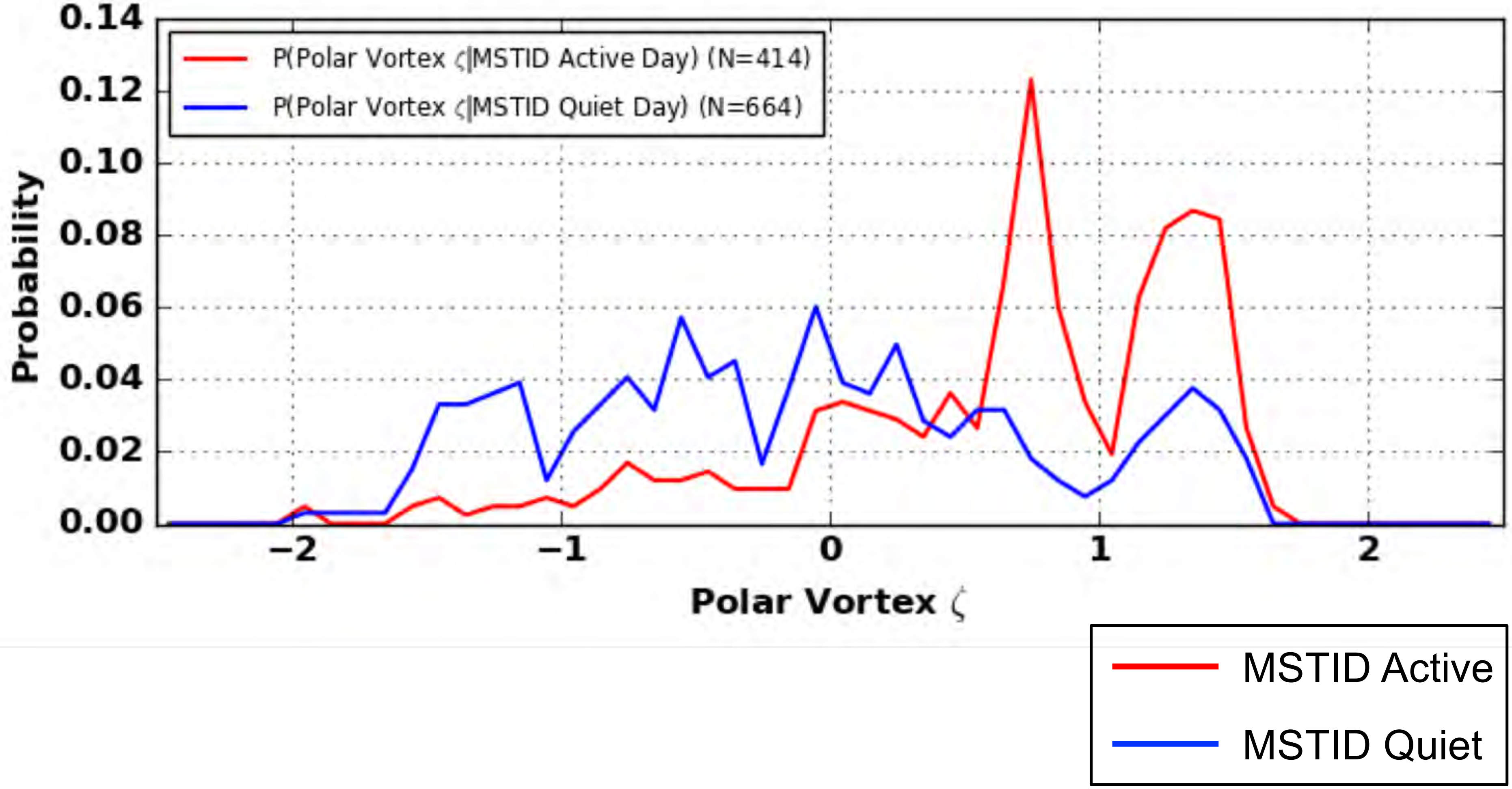


MSTIDs Nov 2012 – May 2013



[Frissell et al., 2016]

Correlation with Polar Vortex!



SuperDARN Achievements

- Hemispheric structure and dynamics of ionospheric convection
- Mesoscale signatures of magnetosphere-ionosphere coupling:
  - Convection vortices associated with field-aligned currents
  - Ionospheric flow bursts associated with transient magnetic reconnection or FTEs
- Inter-hemispheric conjugacy of ionospheric convection
- Convection associated with auroral substorms
- Ionospheric irregularities and high latitude plasma structures (patches)
- Electromagnetic waves: MHD, ULF, Magnetic Field Line Resonances
- Neutral atmosphere: Gravity waves, mesospheric winds, planetary waves
- More generally, SuperDARN convection patterns have been widely used to interpret localized features in other ground and space-based datasets

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Ionospheric Modification

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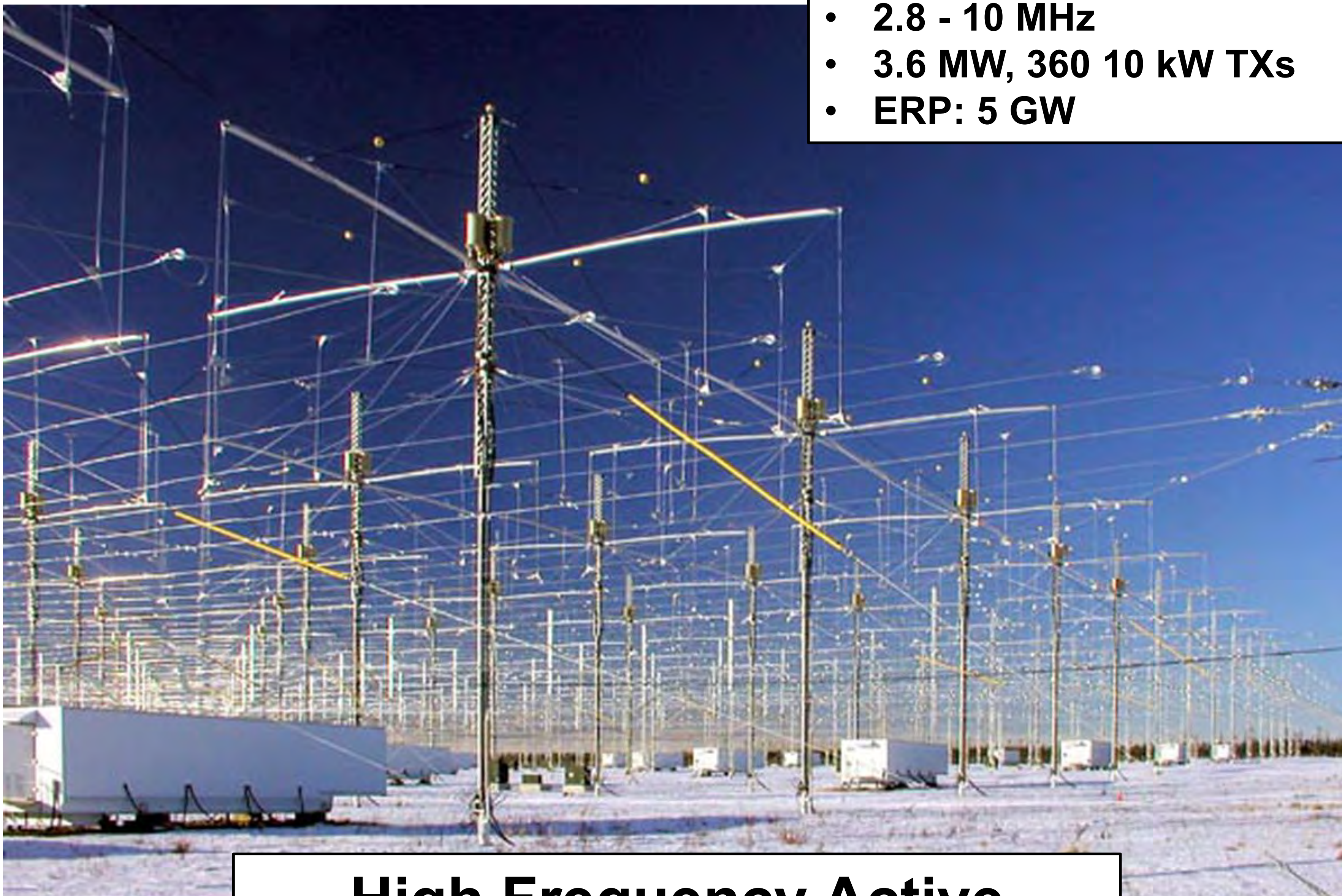
Ionospheric Modification (Heating)

- HF ionospheric heaters can turn the ionosphere into a plasma-physics laboratory
- Electron acceleration processes
- Ionospheric structure irregularities at meter to sub-kilometer scales
- Electron thermal balance
- Resonant ion oscillations
- Airglow optical emissions (artificial aurora)
- Generation of ELF and ULF (Submarine communication)
- Enhanced plasma lines

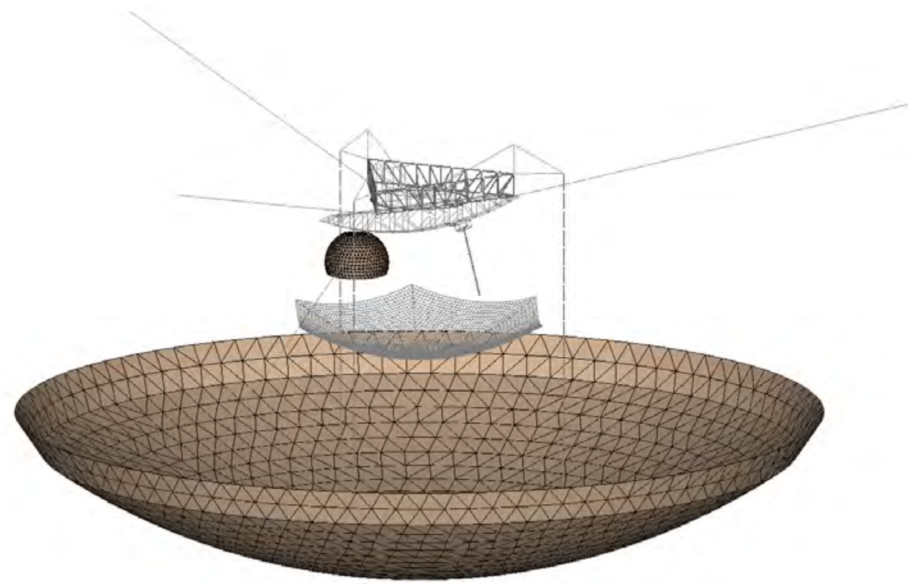
HAARP

- Gakona, AK
- 180 crossed dipole (12 x 15)
- 2.8 - 10 MHz
- 3.6 MW, 360 10 kW TXs
- ERP: 5 GW



High Frequency Active Auroral Research Program

Arecibo



James K. Breakall, WA3FET

- ERP(5.1 MHz) = 99.6 MW (600kW TX power)
- ERP(8.175 MHz) = 212.9 MW (600kW TX power)

Signals of Opportunity

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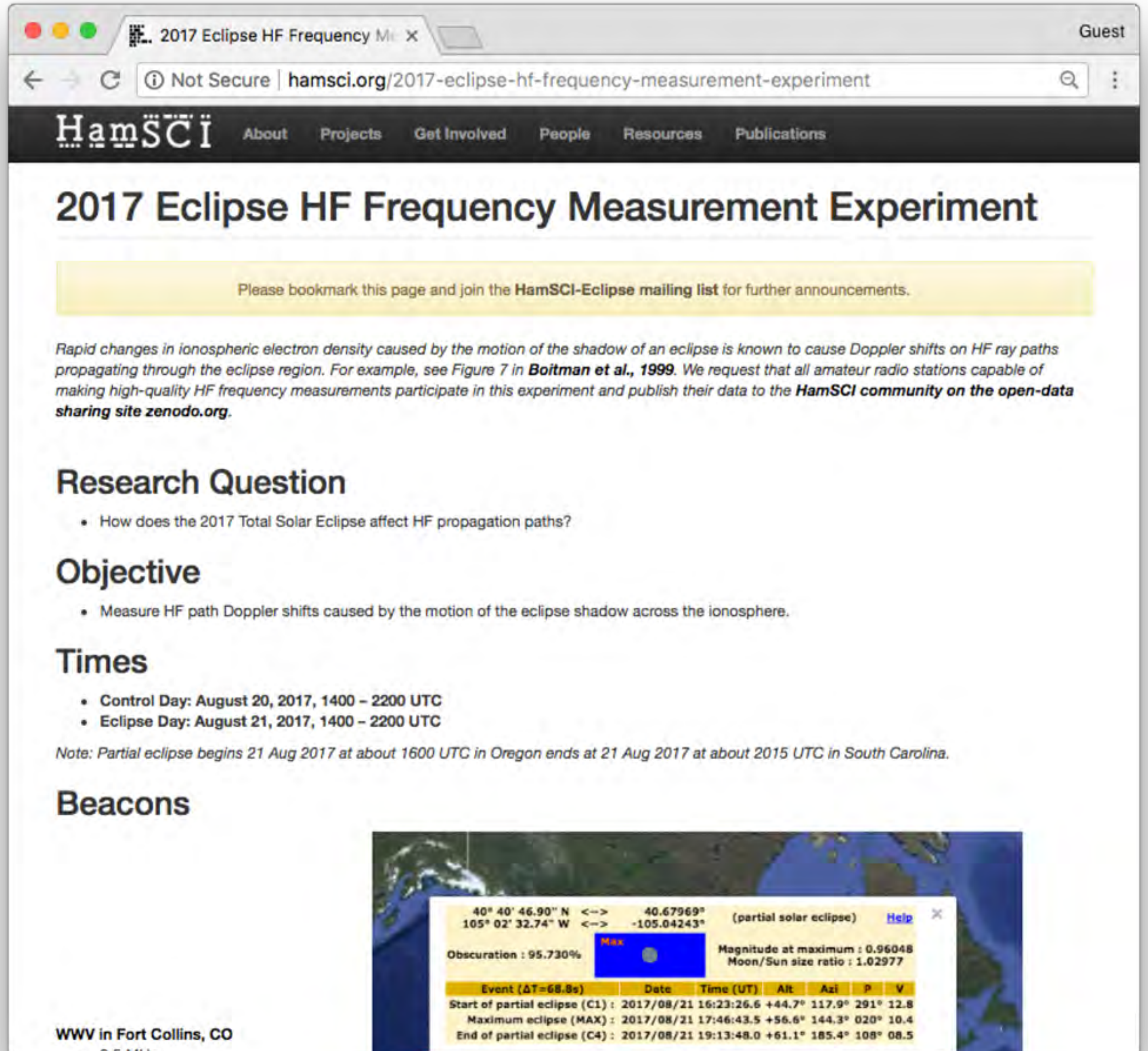
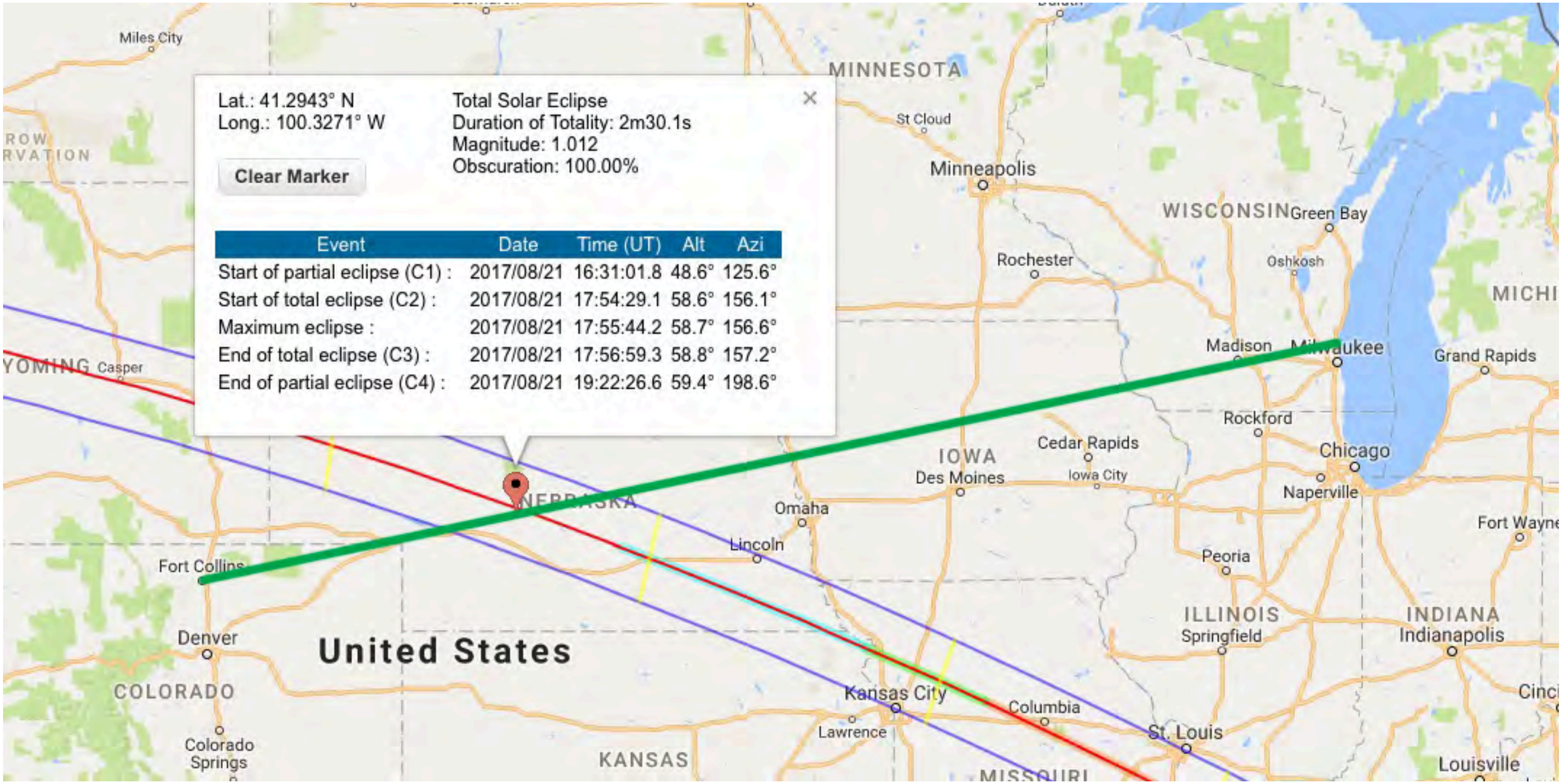
Signals of Opportunity

- Many ionospheric experiments require a transmitter
- Transmitters are often inconvenient
  - Licensing Issues
  - Spectrum Management Considerations
  - Power Limitations
  - Space Limitations
- So, just listen to someone else's transmitter…
  - WWV/CHU HF Standards Stations
  - CODAR HF Ocean Radars
  - Broadcast Radio Stations
  - VLF Transmitters

HF Frequency Measurement Experiment



WA9VNJ 10MHz WWV Observations

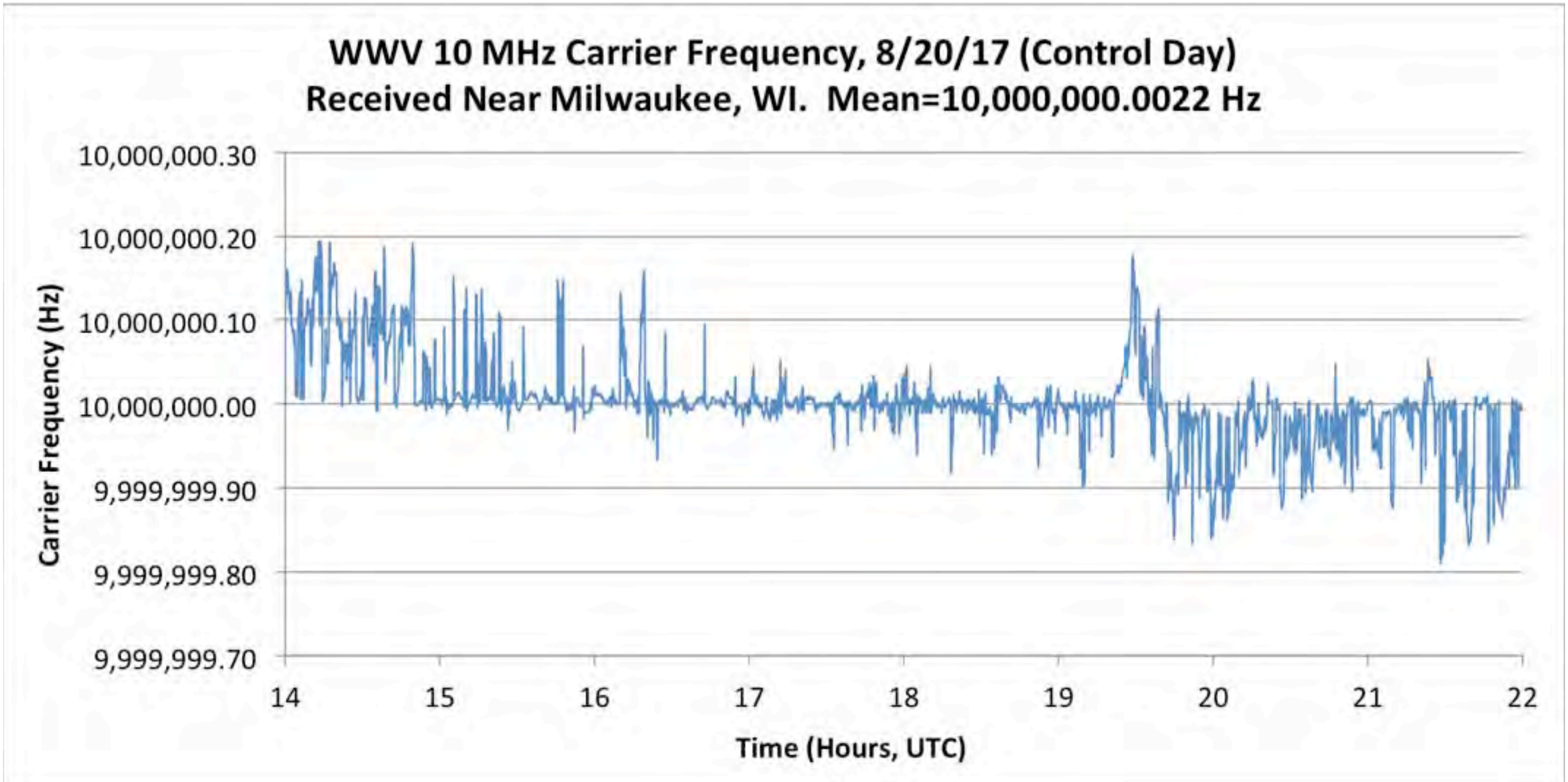


(Measurements by Steve Reyer, WA9VNJ)

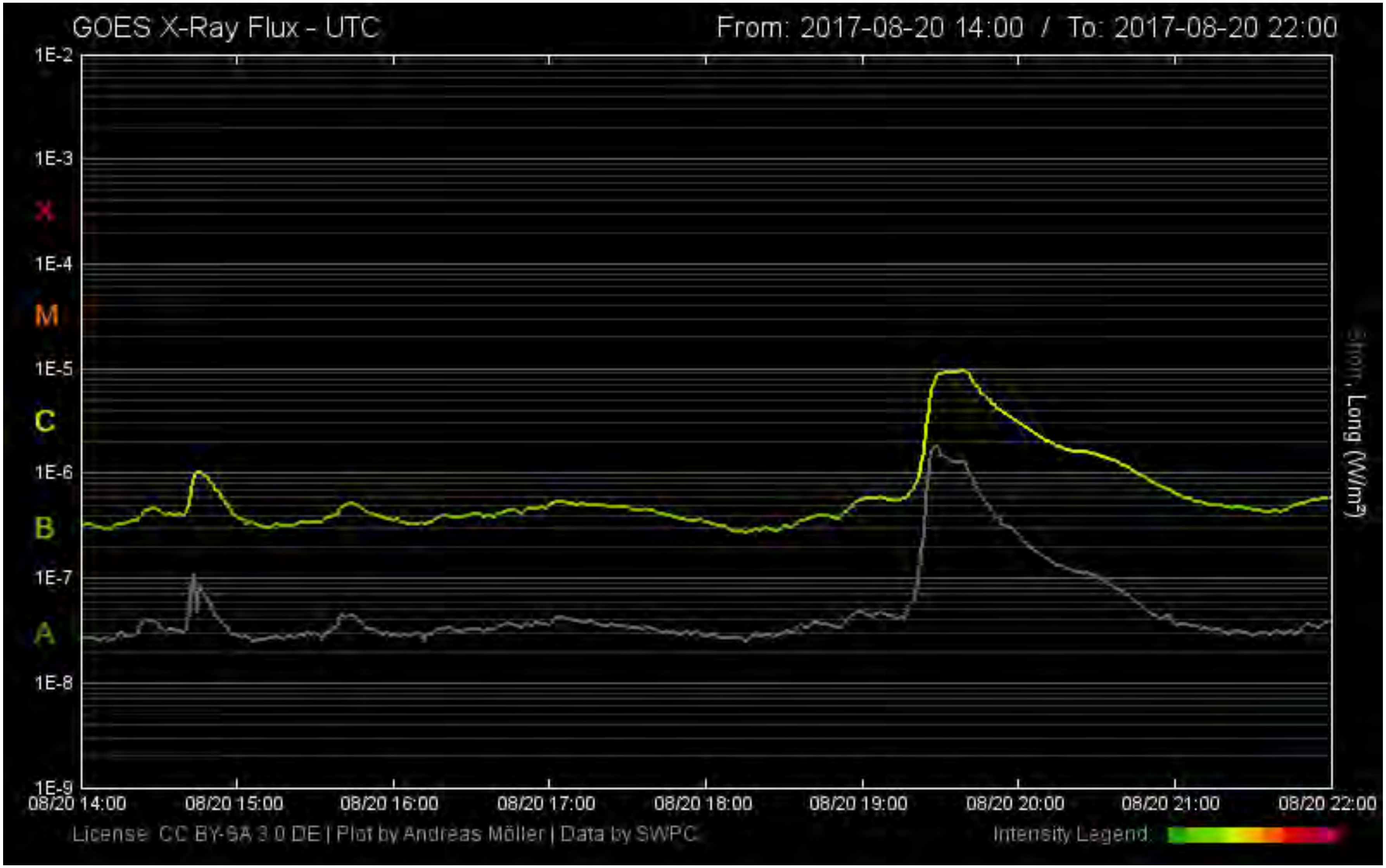
WA9VNJ Instrumentation

- **Radio:** Yaesu FT-857D with XRef-FT oscillator interface driven by a Trimble Thunderbolt GPSDO
- **Calibration:** Rigol DG1022Z signal generator locked to a second TBolt for reference signals.
- **Antenna:** DX Engineering RF-PRO-1B aimed N-S
- **Software:** Spectrum Lab (SL) and custom DSP software.

WA9VNJ 10MHz WWV Observations

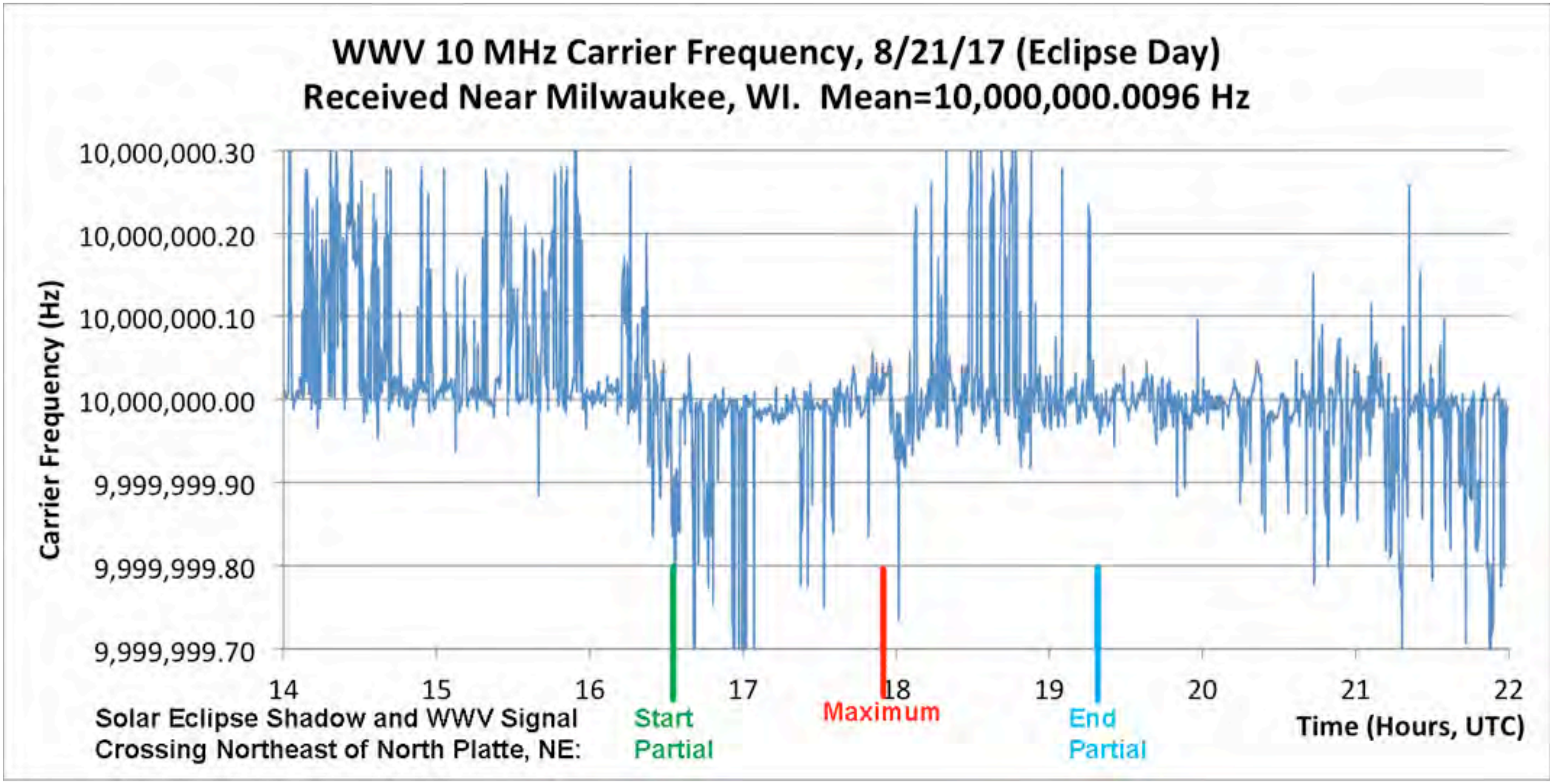


GOES X-Ray Flux – Control Day



http://www.polarlicht-vorhersage.de/goes_archive

WA9VNJ 10MHz WWV Observations



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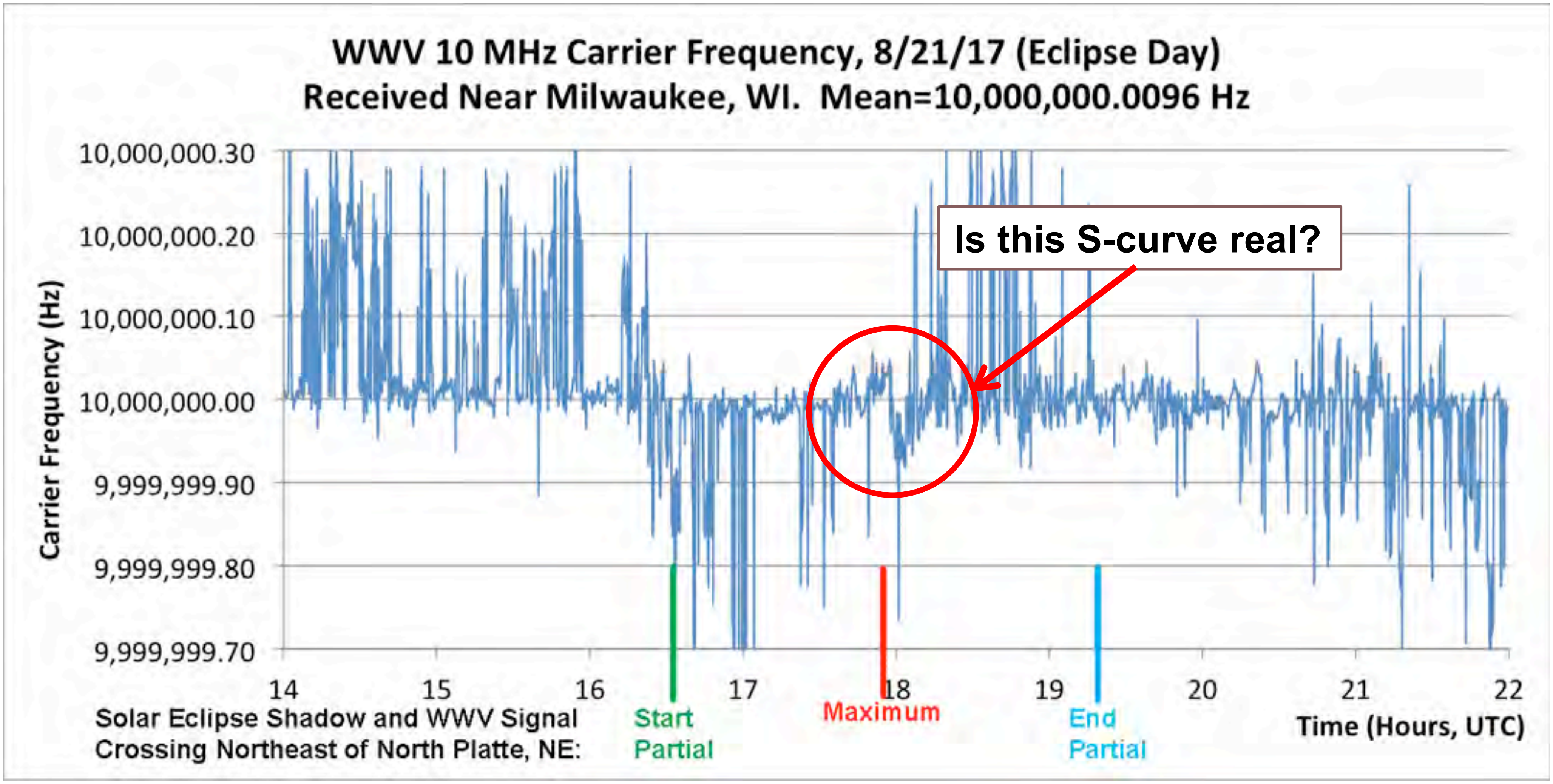
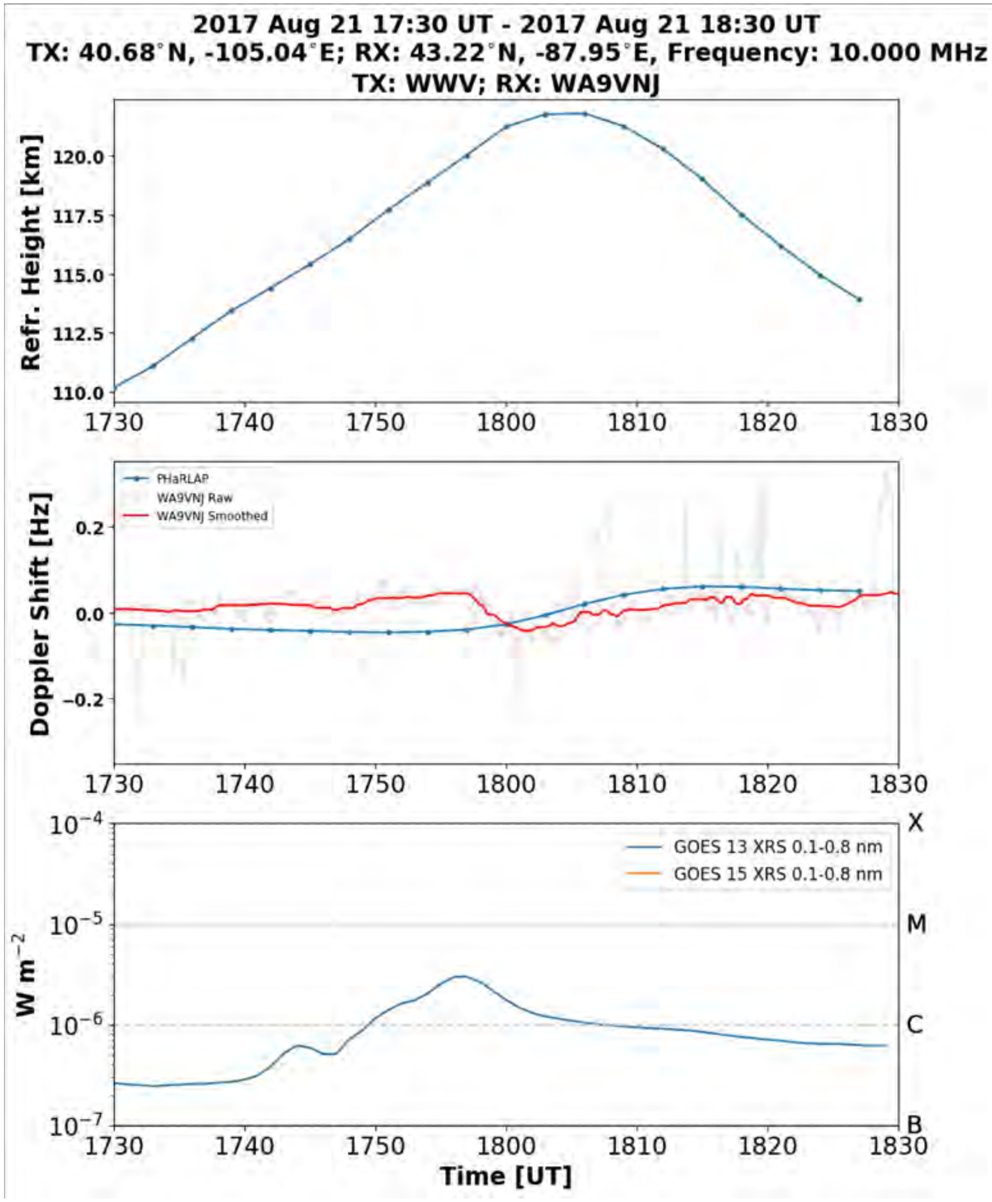
WA9VNJ 10MHz WWV Observations



WA9VNJ/PHaRLAP/GOES



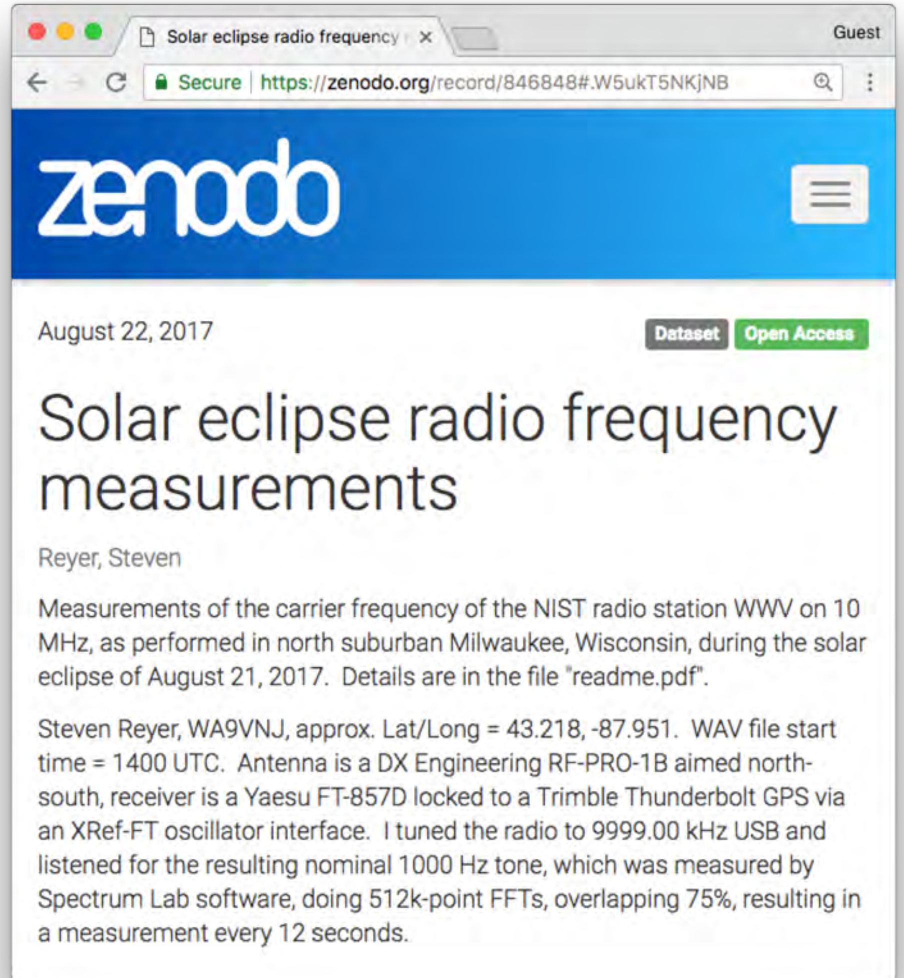
PHaRLAP/SAMI3

WA9VNJ
PHaRLAP/SAMI3

GOES X-RAY

WA9VNJ Conclusions

- Doppler shifts observed for
  - Dawn and Dusk
  - Eclipse Onset and Recovery
  - Solar Flares
- Small solar flares can have a pronounced effect
  - C2-Class flare caused 0.05 Hz shift!
- We don't understand the short-term variability.



Solar eclipse radio frequency

Guest

Secure | https://zenodo.org/record/846848#.W5ukT5NKjNB

zenodo

August 22, 2017

Dataset Open Access

Solar eclipse radio frequency measurements

Reyer, Steven

Measurements of the carrier frequency of the NIST radio station WWV on 10 MHz, as performed in north suburban Milwaukee, Wisconsin, during the solar eclipse of August 21, 2017. Details are in the file "readme.pdf".

Steven Reyer, WA9VNJ, approx. Lat/Long = 43.218, -87.951. WAV file start time = 1400 UTC. Antenna is a DX Engineering RF-PRO-1B aimed north-south, receiver is a Yaesu FT-857D locked to a Trimble Thunderbolt GPS via an XRef-FT oscillator interface. I tuned the radio to 9999.00 kHz USB and listened for the resulting nominal 1000 Hz tone, which was measured by Spectrum Lab software, doing 512k-point FFTs, overlapping 75%, resulting in a measurement every 12 seconds.

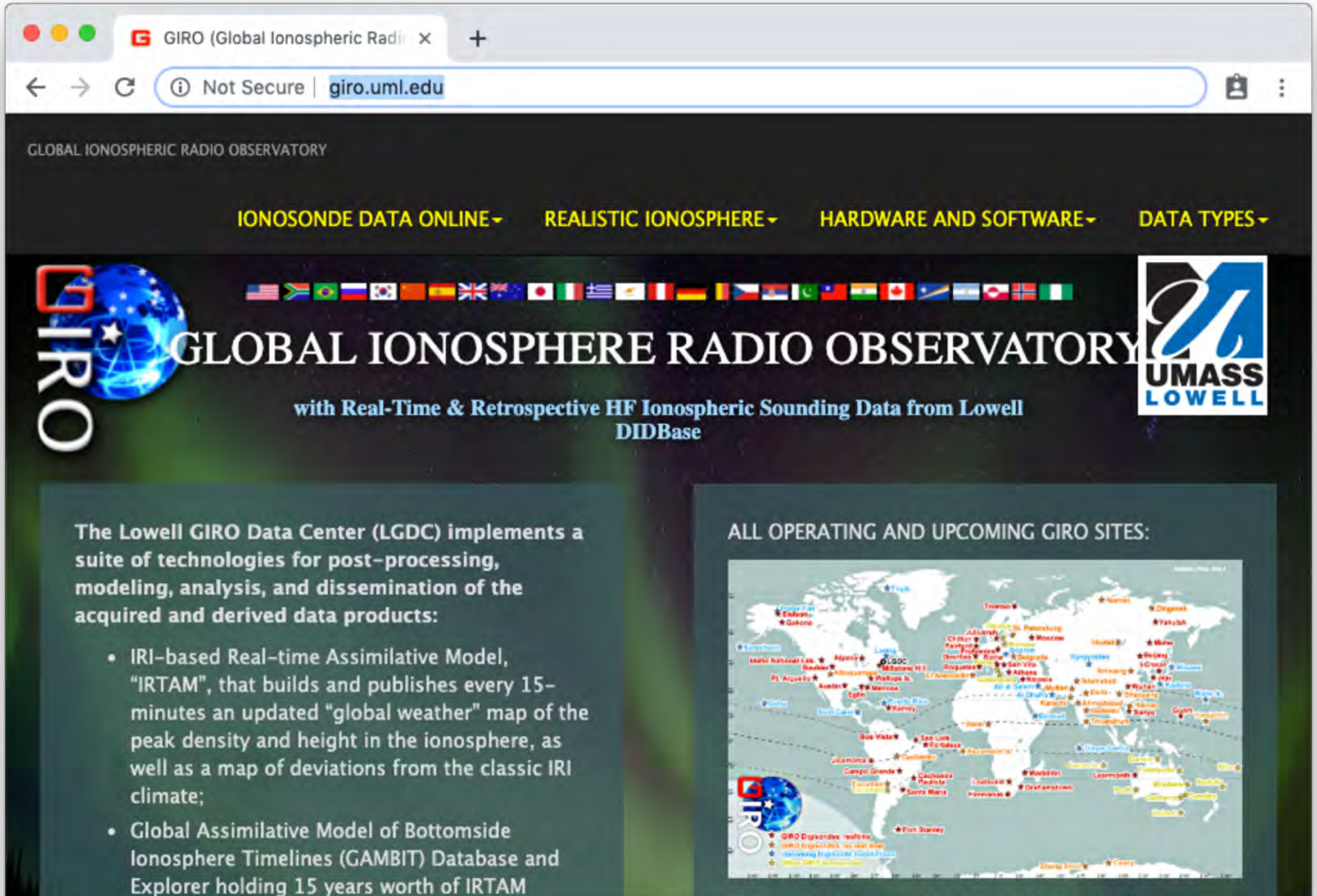
https://zenodo.org/communities/hamsci

Data Websites

frissell@njit.edu

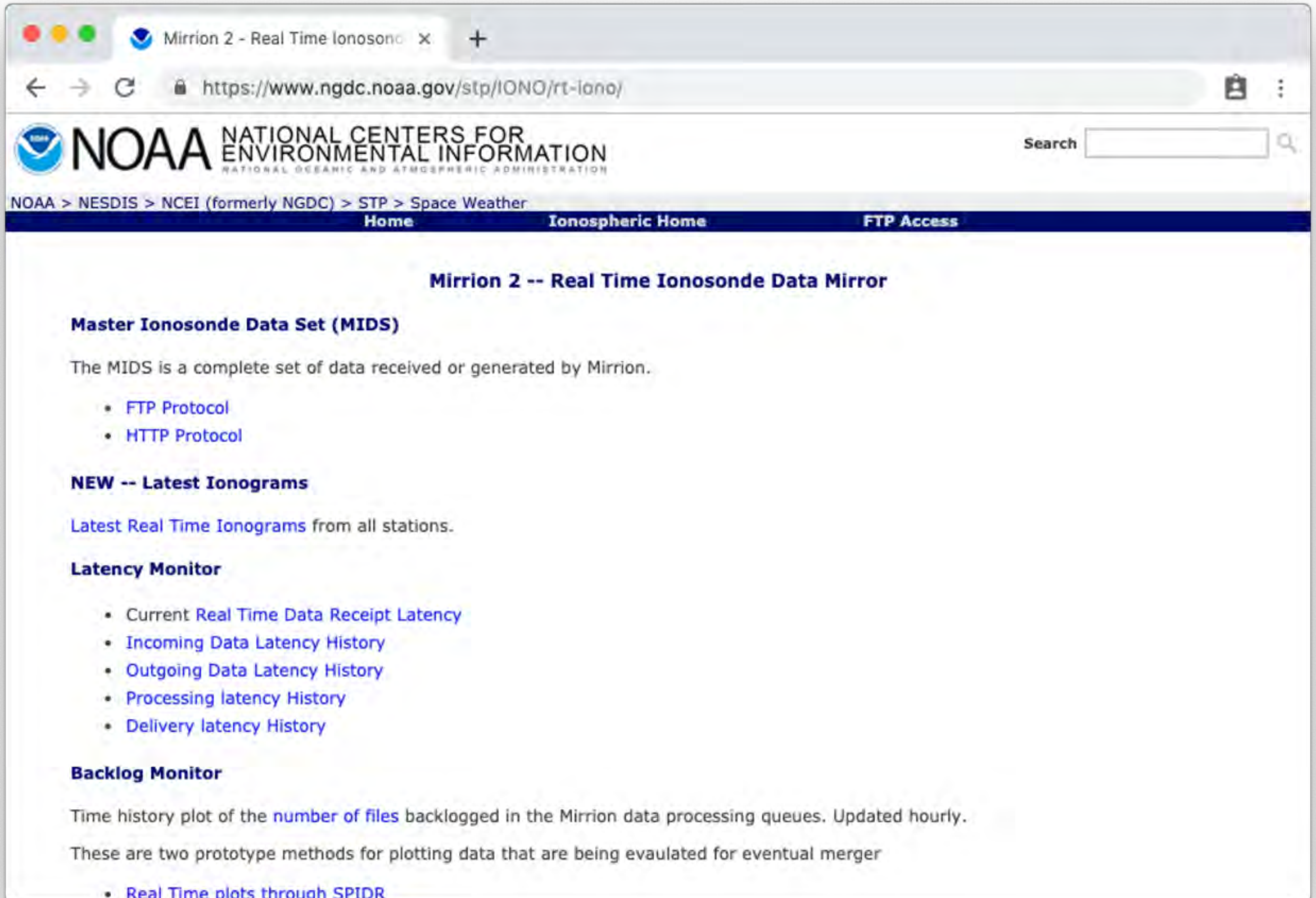
Ionogram Data Access

http://giro.uml.edu/



Ionogram Data Access

https://www.ngdc.noaa.gov/stp/IONO/rt-iono/



Mirrion 2 - Real Time Ionosonde

https://www.ngdc.noaa.gov/stp/IONO/rt-iono/

NOAA NATIONAL CENTERS FOR ENVIRONMENTAL INFORMATION
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Search

NOAA > NESDIS > NCEI (formerly NGDC) > STP > Space Weather

Home | Ionospheric Home | FTP Access

Mirrion 2 -- Real Time Ionosonde Data Mirror

Master Ionosonde Data Set (MIDS)

The MIDS is a complete set of data received or generated by Mirrion.

- FTP Protocol
- HTTP Protocol

NEW -- Latest Ionograms

Latest Real Time Ionograms from all stations.

Latency Monitor

- Current Real Time Data Receipt Latency
- Incoming Data Latency History
- Outgoing Data Latency History
- Processing latency History
- Delivery latency History

Backlog Monitor

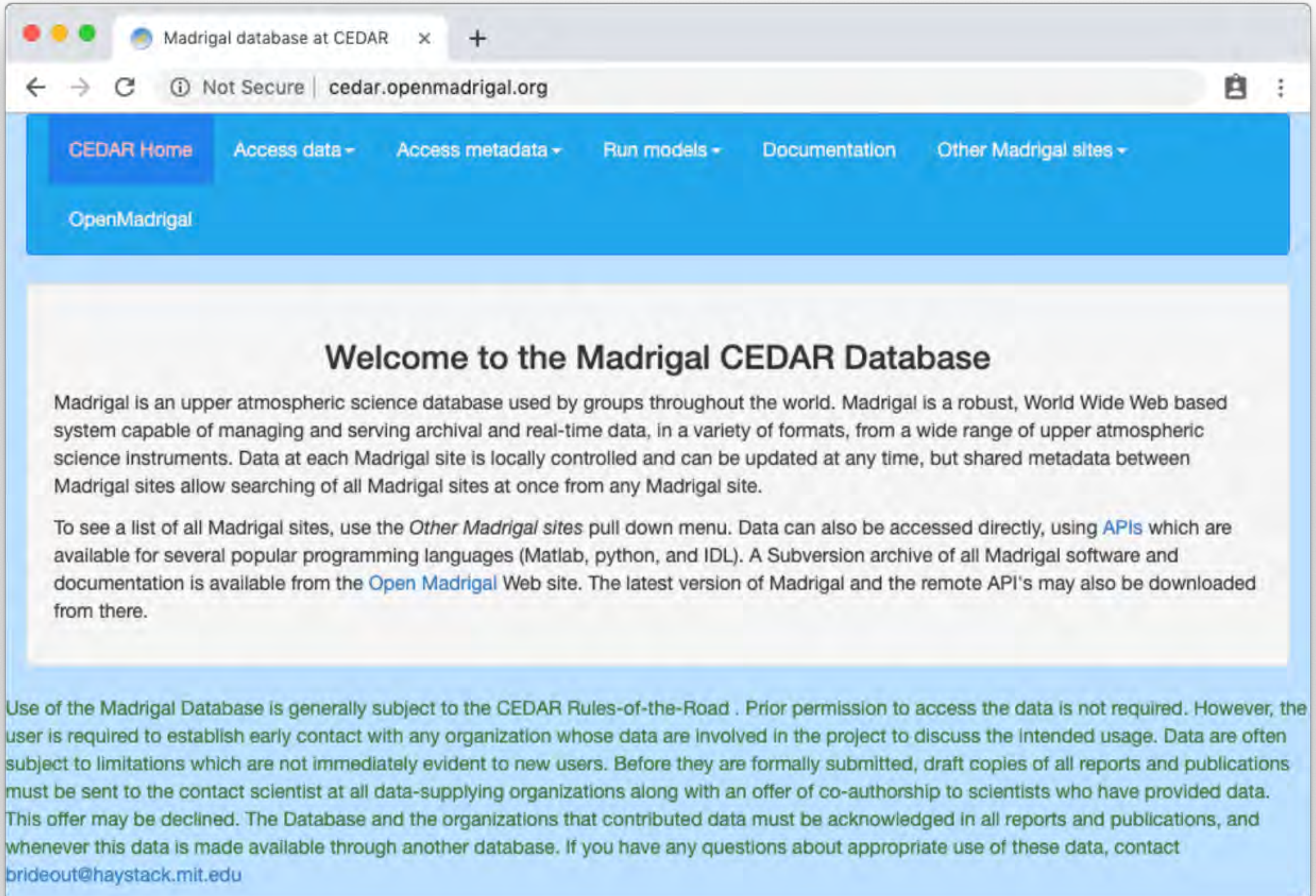
Time history plot of the number of files backlogged in the Mirrion data processing queues. Updated hourly.

These are two prototype methods for plotting data that are being evaulated for eventual merger

- Real Time plots through SPIDR

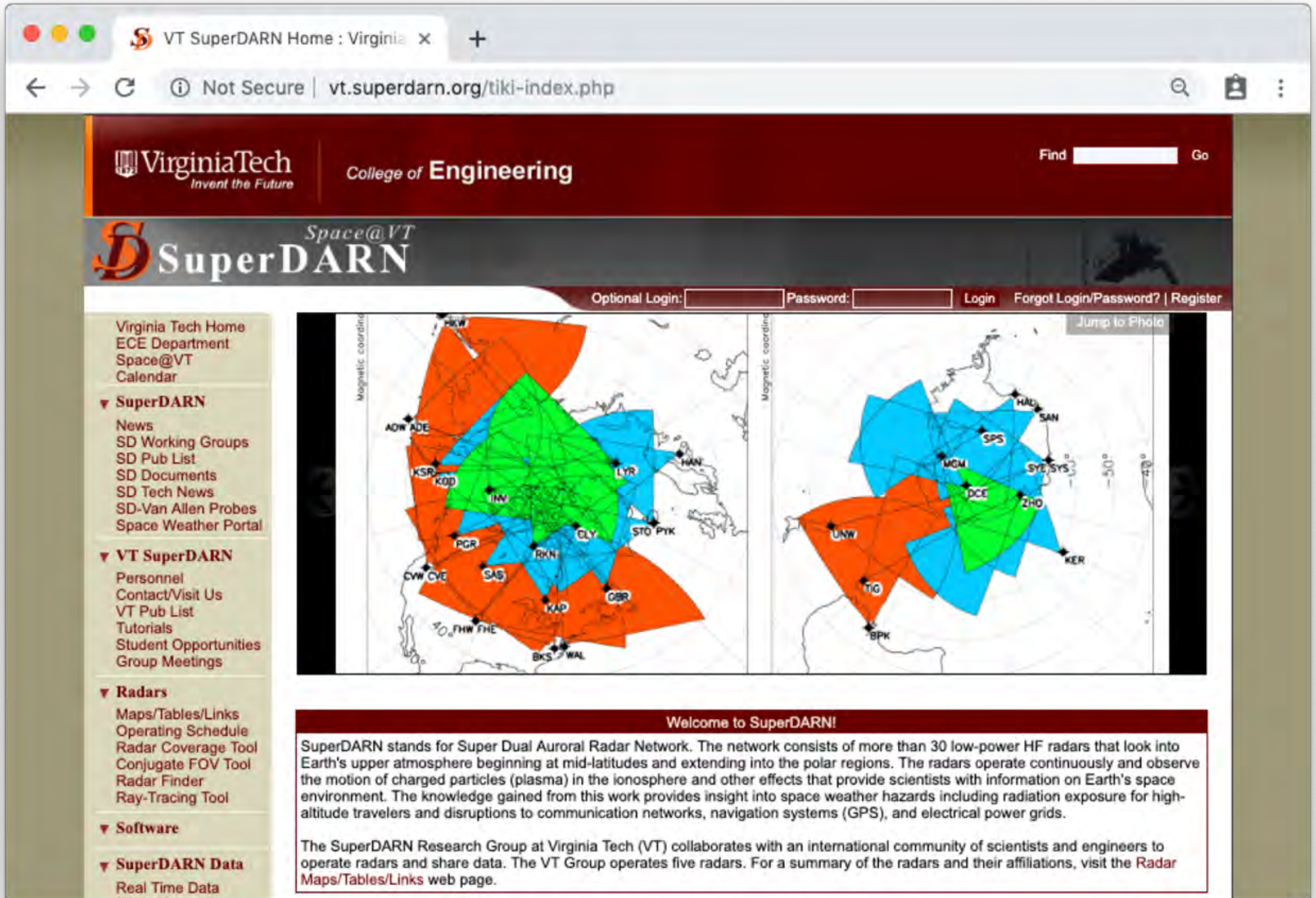
ISR & GPS TEC Data

http://cedar.openmadrigal.org



SuperDARN Data Access

http://vt.superdarn.org



Thank you!

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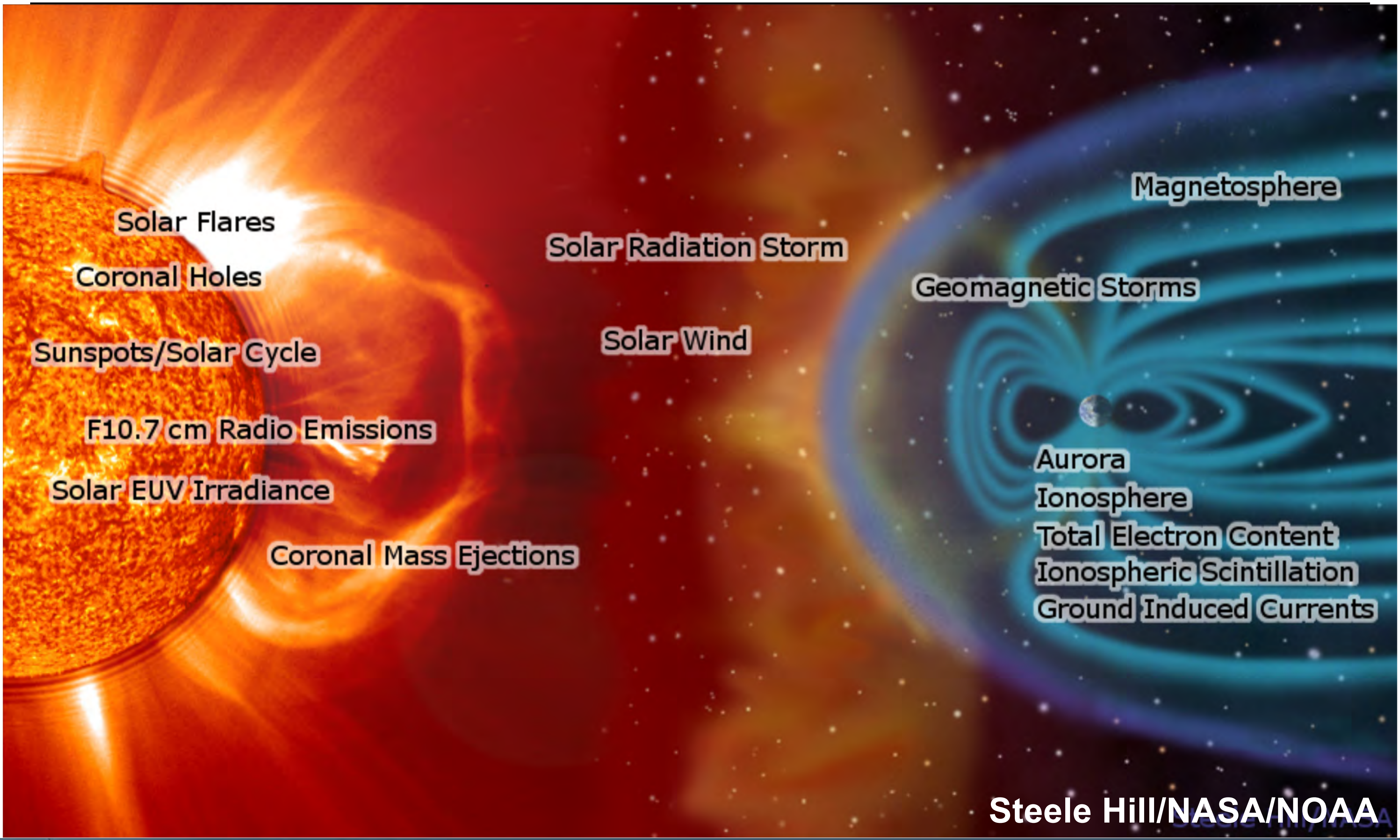
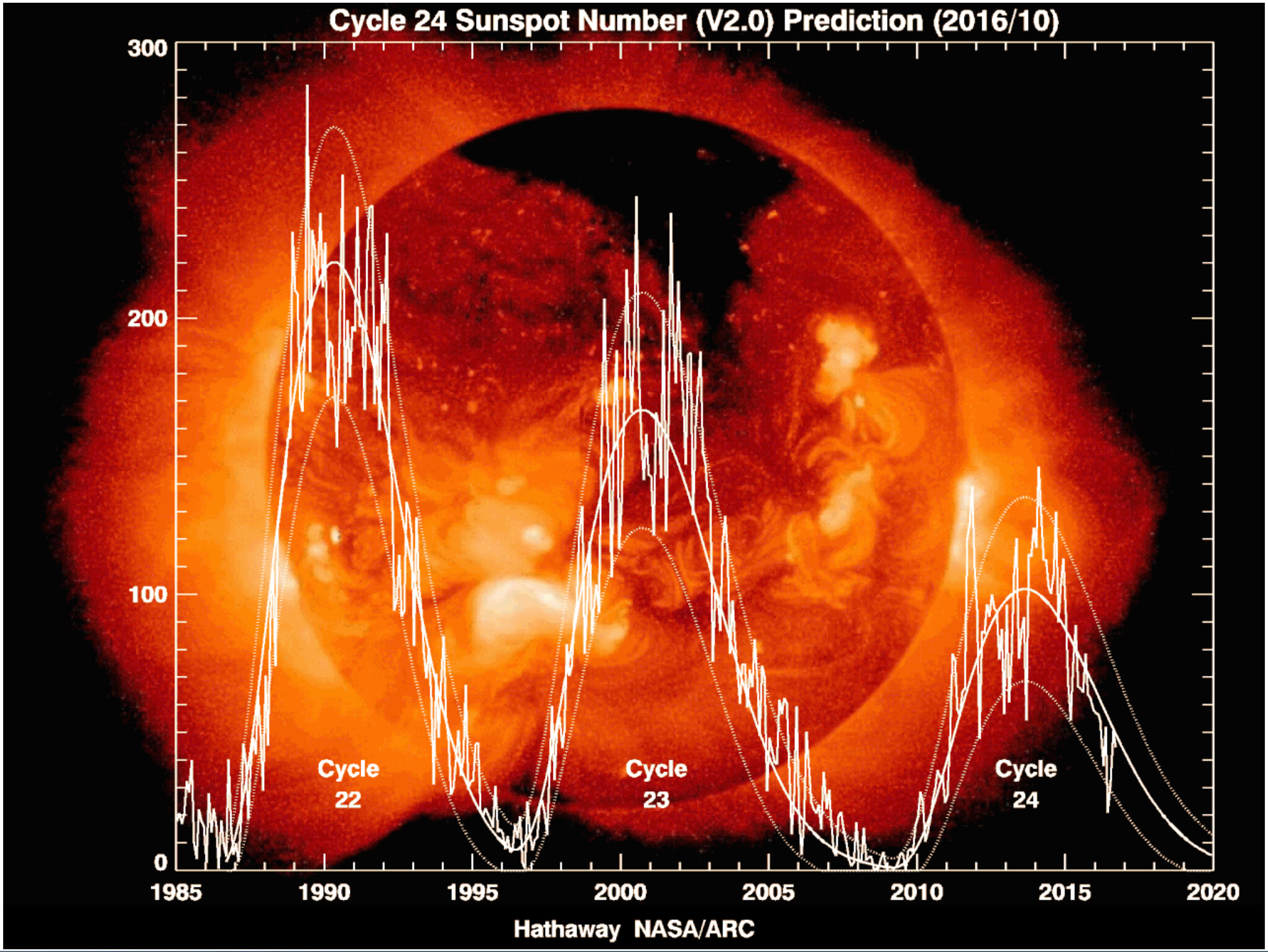
Acknowledgements

- Space Weather Effects on Radio Communication and GNSS Lecture by Geoff Hughes, 2018 Boulder Space Weather Summer School
- UNIS Lectures on Ionospheric Radars by Kjellmar Oksavik and Katie Herlingshaw
- Arecibo Heating Antenna HamSCI Workshop 2019 presentation by Jim Breakall
- Other sources as referenced

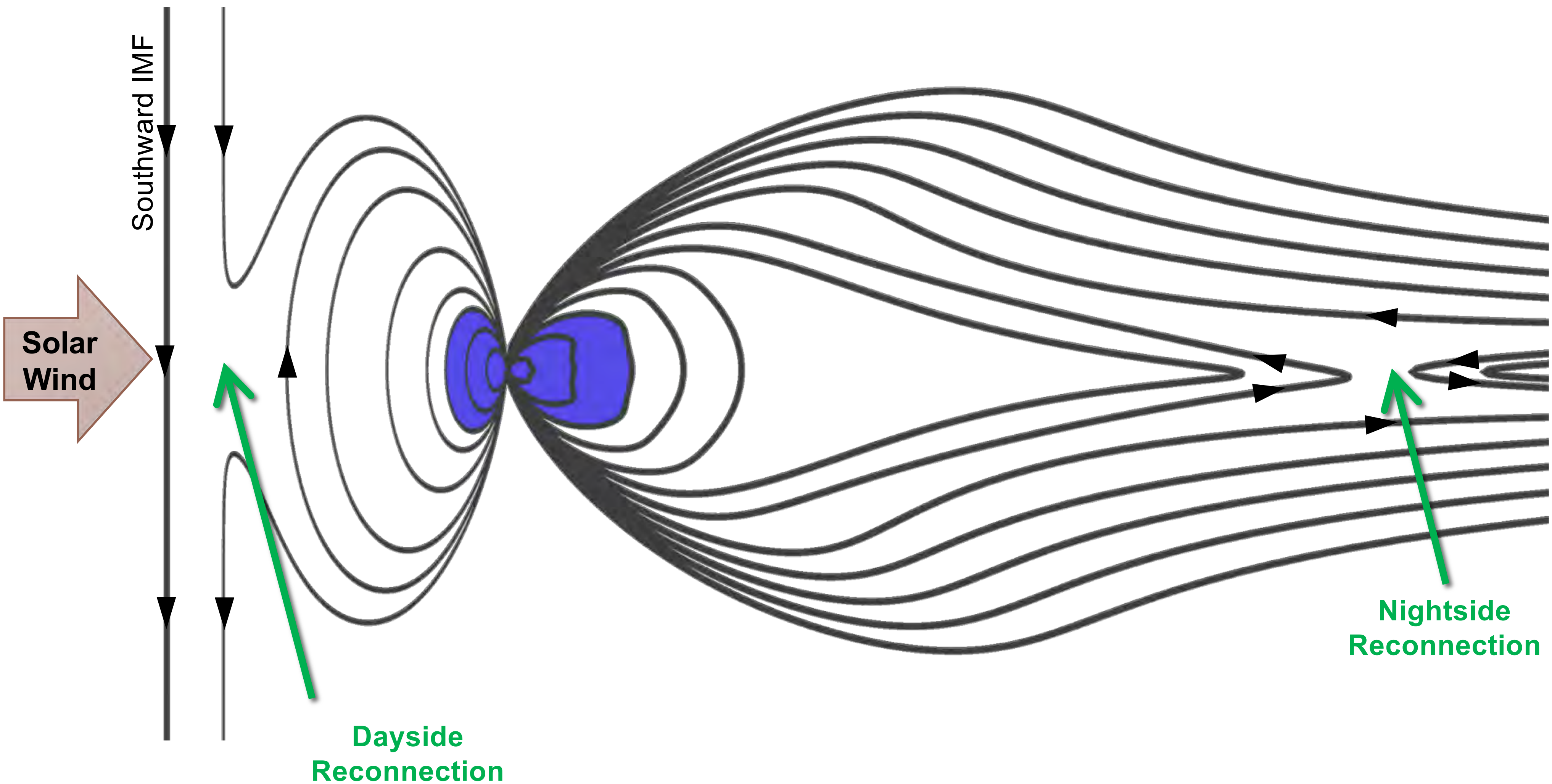
Solar-Terrestrial Environment



Sunspot Cycle

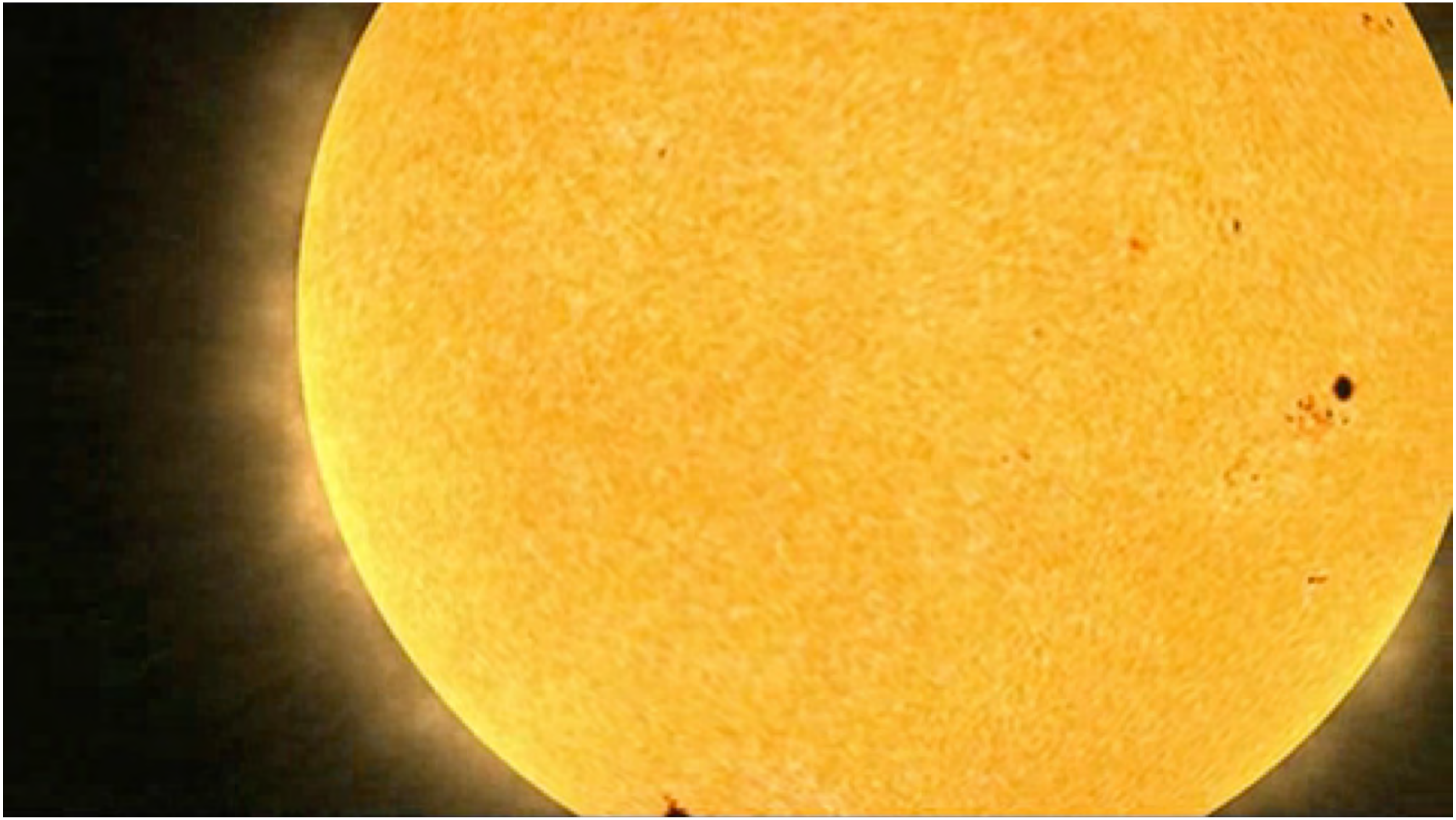


Getting Energy into the Magnetosphere



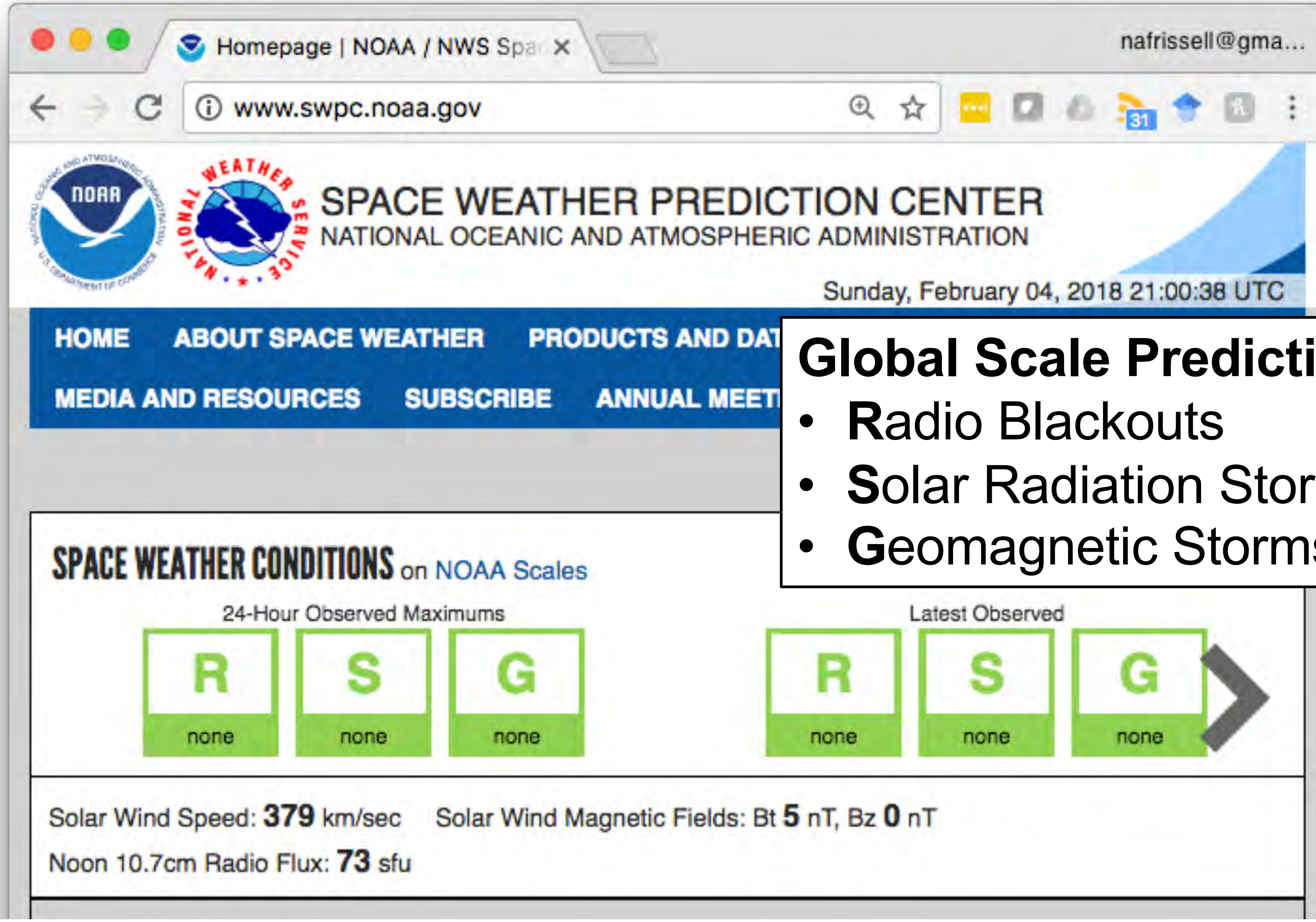
[Frissell, 2016, Dissertation]

Substorms



[Visualization by NASA]

NOAA Space Weather Prediction Center

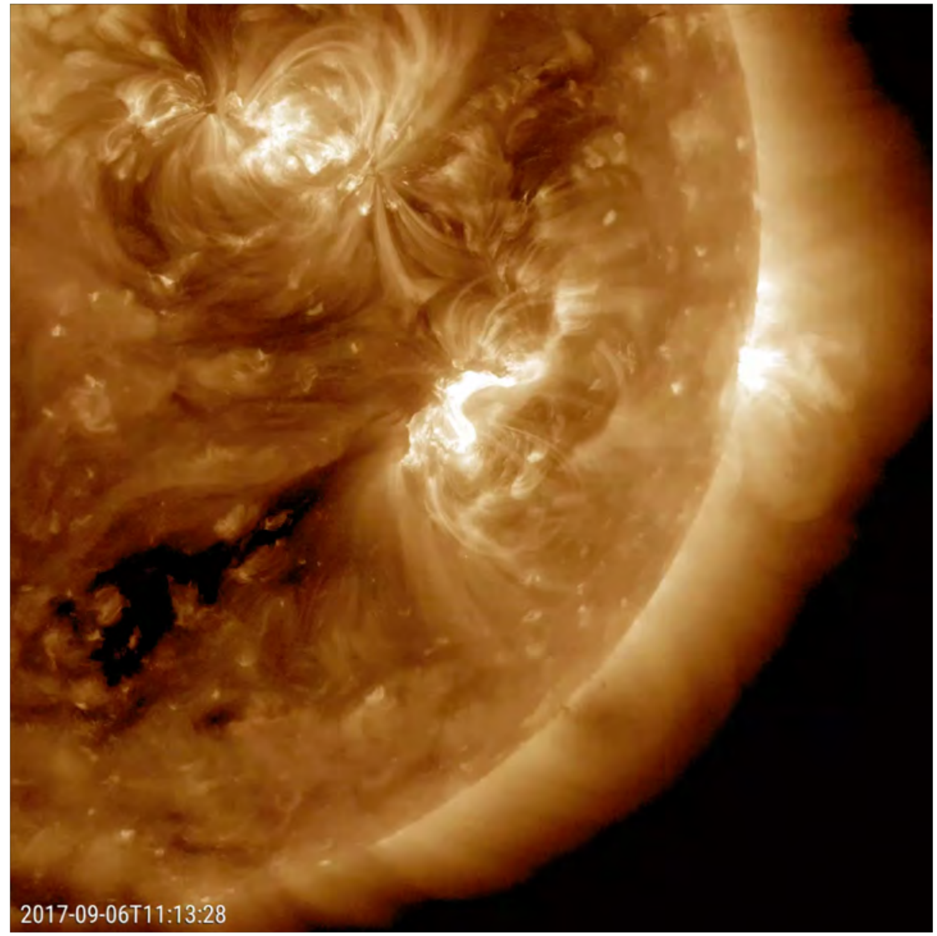


Global Scale Predictions

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

Solar Flares

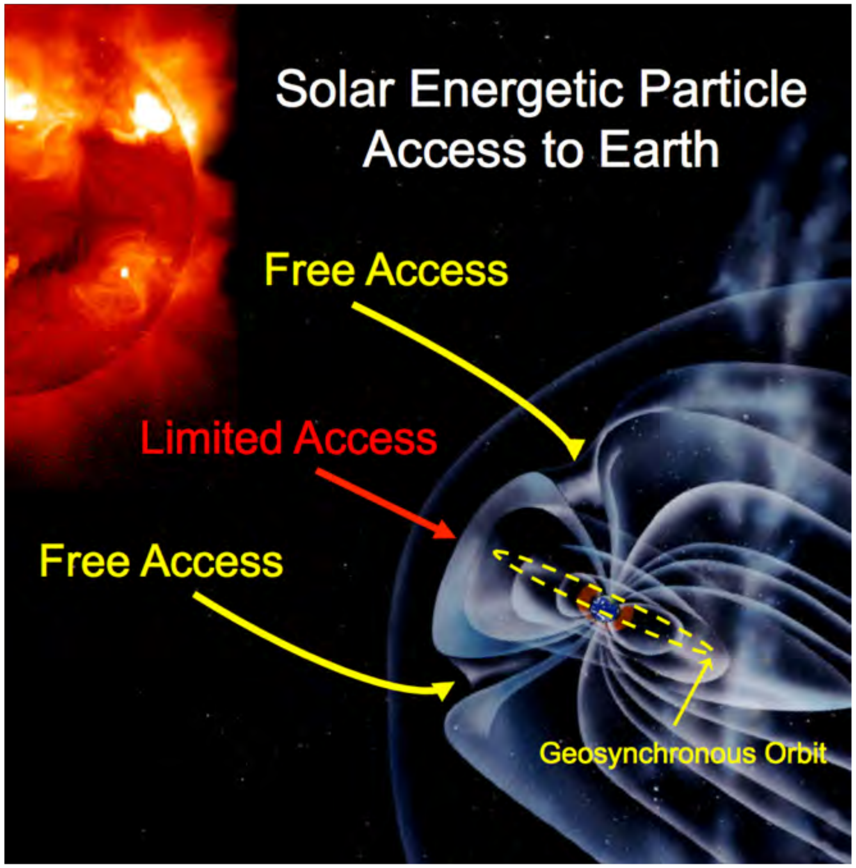
- Sudden increase in electromagnetic energy from localized regions on the sun.
- Energy travels at the speed of light (8 min to Earth)
- Soft X-Ray (0.1-0.8 nm) Earthward-directed energy can cause HF radio blackouts.
- Often, but not always, accompanied by a CME.



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

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

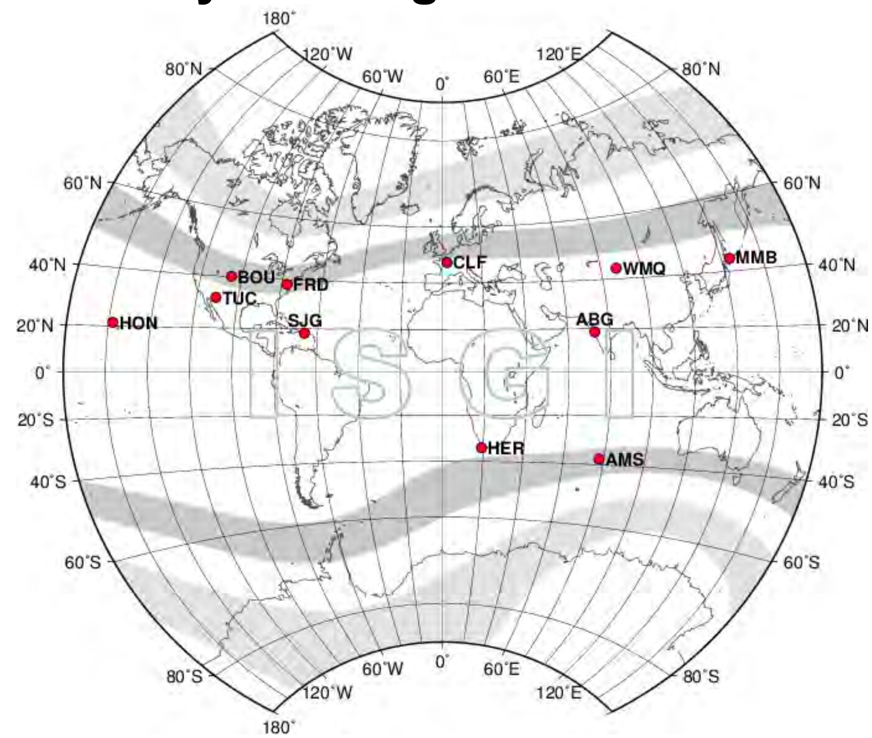


[NASA / Annotated by H. Singer]

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