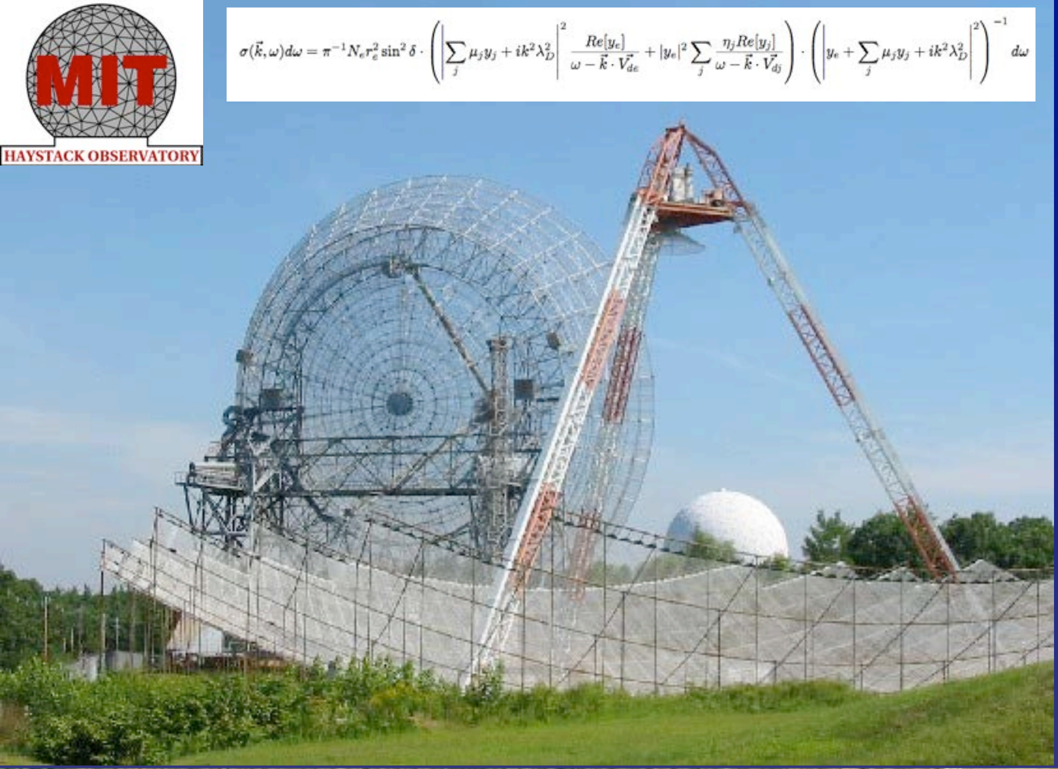
HAYSTACK OBSERVATORY

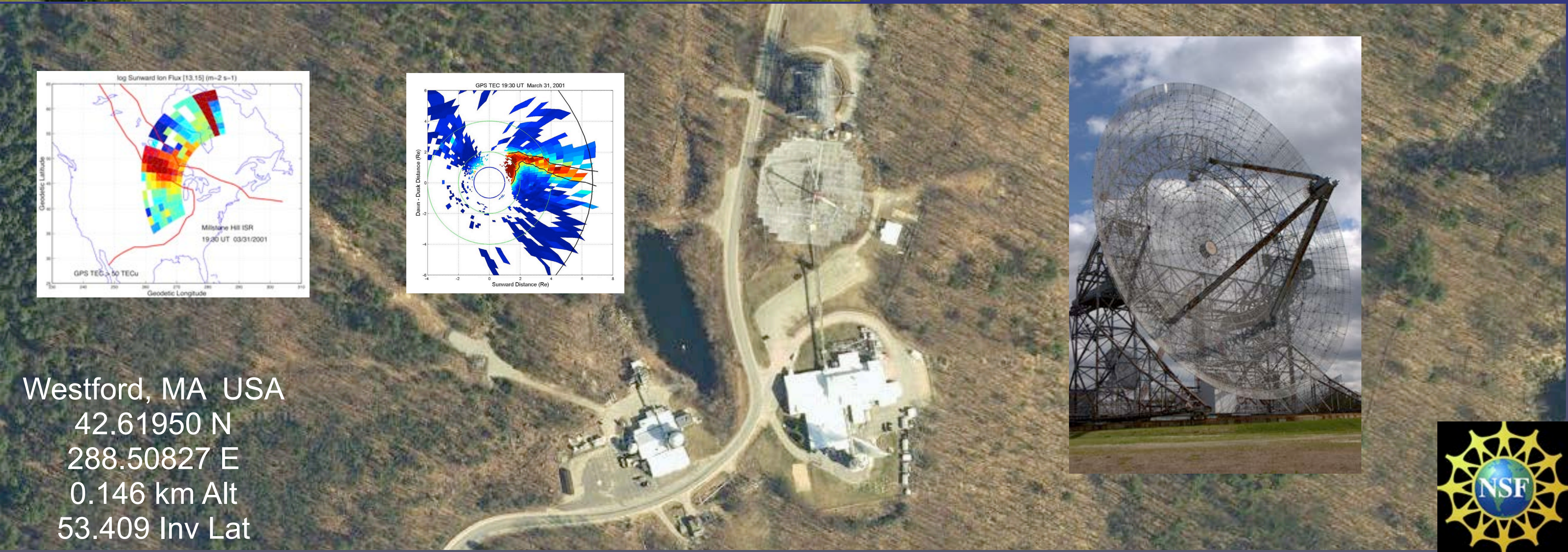
$$\sigma(\vec{k},\omega)d\omega = \pi^{-1}N_e r_e^2 \sin^2\delta \cdot \left(\left|\sum_j \mu_j y_j + ik^2\lambda_D^2\right|^2 \frac{Re[y_e]}{\omega - \vec{k}\cdot\vec{V_{de}}} + |y_e|^2 \sum_j \frac{\eta_j Re[y_j]}{\omega - \vec{k}\cdot\vec{V_{dj}}}\right) \cdot \left(\left|y_e + \sum_j \mu_j y_j + ik^2\lambda_D^2\right|^2\right)^{-1} d\omega$$



Incoherent Scatter Radar: Remote Sensing of Earth's Upper Atmosphere

Dr. P. J. Erickson
Atmospheric Sciences Group
MIT Haystack Observatory

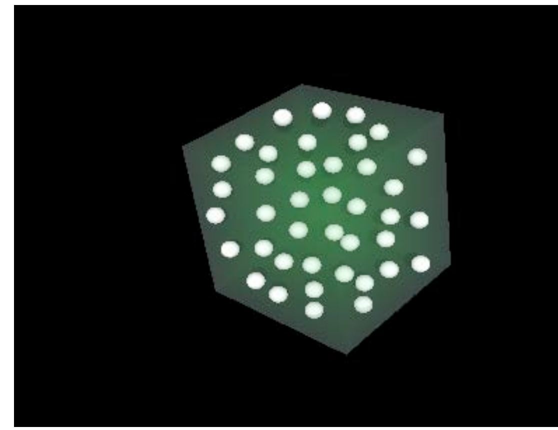
CEDAR 2014 Student Workshop
June 22, 2014
Seattle, WA



Westford, MA USA
42.61950 N
288.50827 E
0.146 km Alt
53.409 Inv Lat

Remote Radar Sensing of Ionospheric Plasma

Sufficiently large systems can use <u>incoherent (Thomson) scatter</u> to measure basic ionospheric physical properties. First done in 1958.



Each scatter event happens only once (no multiple scattering to worry about; not a thick/opaque medium)

Free electron scatter, restrained by ions

Very low radar cross section (RCS): < -50 dBsm

Gaussian random process: statistical experiment

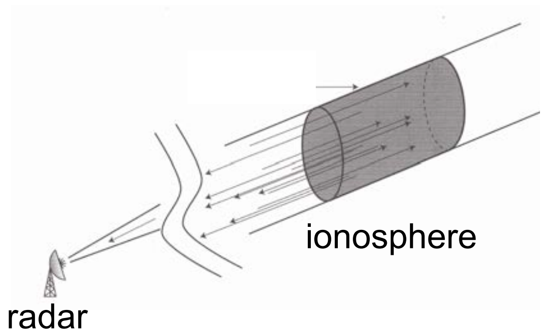
Very weak scatter : Challenge.

Benefit: entire ionospheric profile accessible - unlike ground based ionosondes, which only sense to F region density peak.

Remote sensing a plasma: The experimental (radar) view

Suppose we transmit a wave towards a plasma and measure the scattered wave:

$$P_{rec} = (P_{inc}) A_{scat} \left(\frac{A_{rec}}{4\pi R^2}\right)$$



$$A_{scat} = \sigma_{radar} V_s$$

(ionosphere is a beam filling target)

$$\sigma_{radar} = 4\pi \sigma_{total}$$

(Solid angle)

$$\left(\frac{P_{rec}}{P_{inc}}\right)\left(\frac{4\pi R^2}{A_{rec}}\right)\left(\frac{1}{V_s}\right) = 4\pi r_e^2 \sin^2 \delta \left\langle |\Delta N(k)|^2 \right\rangle$$

Measurable experimentally

The physics lies here..

Random fluctuations of electrons (function of wavelength)

Scattering Model

Plasmas (ionosphere) are thermal gases and $\Delta N(\vec{r}, t)$ is a Gaussian random variable, so the Central Limit Theorem applies:

statistical average → $$\langle E_s(t) \rangle = \langle \Delta N(\vec{r}, t) \rangle = 0$$

It's much more useful to look at second order products – in other words, examine <u>temporal correlations</u> in the scattered field:

$$\langle E_s(t)\ E_s^*(t+\tau) \rangle \propto\ e^{-j\omega_0 \tau} \left\langle \Delta N(\vec{k}, t)\ \Delta N^*(\vec{k}, t+\tau) \right\rangle$$

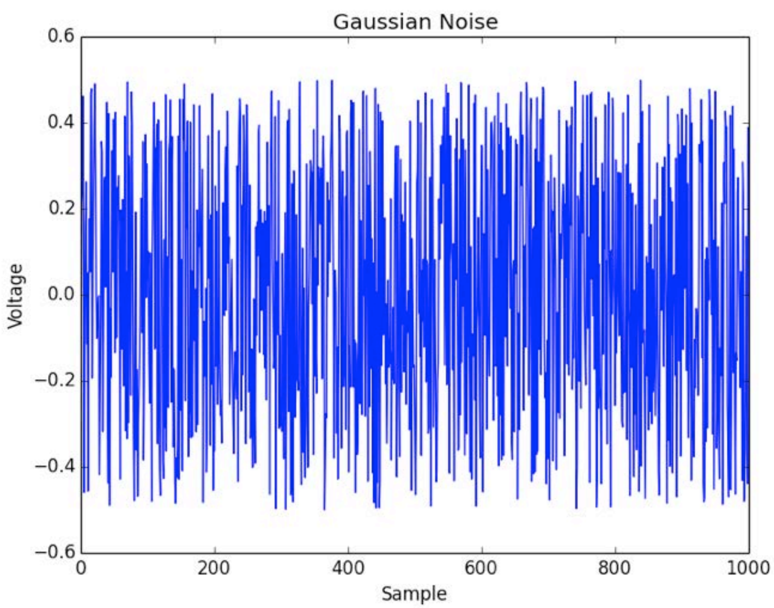
power spectral version:

$$\langle E_s(t) E_s^*(t+\tau) \rangle \rightarrow \left\langle \left| \Delta N(\vec{k}, w) \right|^2 \right\rangle$$

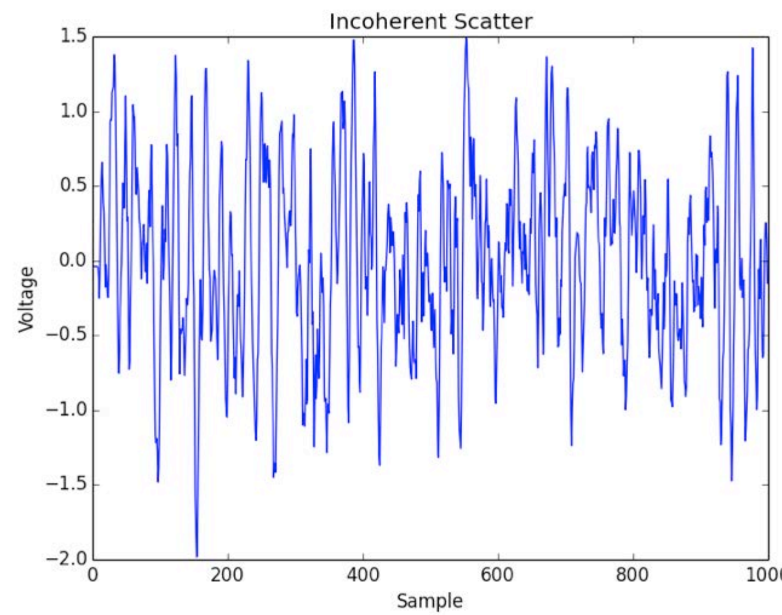
set by your transmitter wavelength (→ $\vec{k}$)

spectral shape: thermal plasma parameters (→ w)

Oscilloscope view of incoherently scattered voltage signal

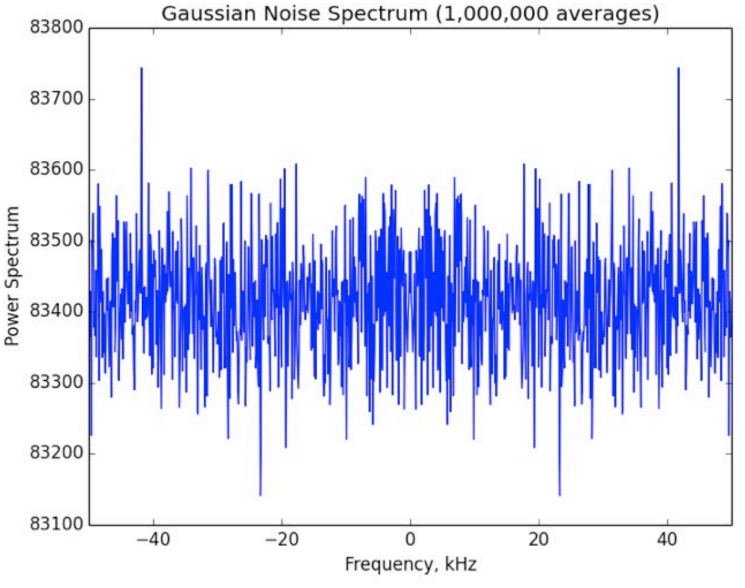


Gaussian random noise
V(t)

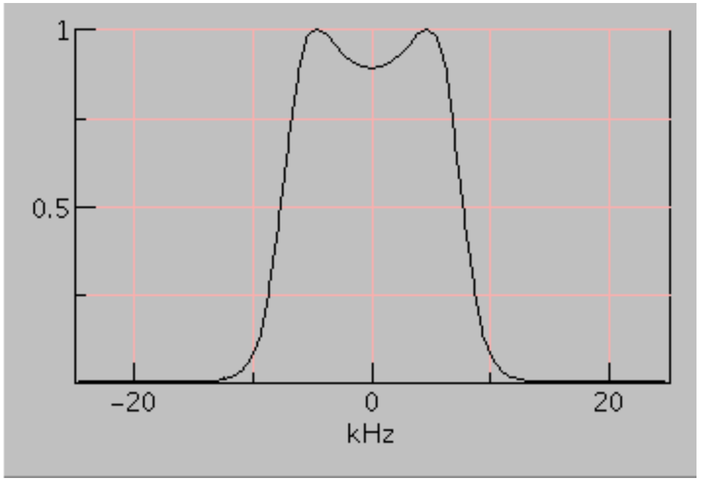


Incoherent scatter signal
V(t)

Spectral view of incoherently scattered voltage signal



Gaussian random noise



Incoherent scatter signal
(real thing would have some variable fluctuations)

Detectability of scatter from ionospheric plasma

Assume a beam filling plasma at F region altitudes (300 km) with very high electron density (1E12 electrons per m3):

Classical electron scattering cross-section $\sigma_e = 10^{-28} m^2 / e^-$

Assume a pulse length of 10 km.
Assume a cross-beam width of 1 km (~ Arecibo).

$$\sigma_{tot} \sim 10^{-6} m^2$$

NB: Born approximation is very valid (single scatter), since total amount of scattered power in the volume ~ 1E-12

Detectability of scatter from ionospheric plasma

For fraction of scattered power actually received, assume isotropic scatter and a BIG 100 meter diameter antenna:

$$f_{rec} = \frac{A_{rec}}{4\pi R^2} \sim \frac{10^4 m}{4(300 \times 10^3 m)^2}$$

About -80 dB (1E-8): not much. So:

$$\frac{P_{rec}}{P_{tx}} \sim 10^{-20}$$

So a radar with 1 MW transmitted signal receives 10 femtowatts of incoherently scattered power from free electrons in the ionosphere.

REALLY not very much.

Detectability of scatter from ionospheric plasma

What matters, though, is the signal to noise ratio:

$$P_{noise} \sim 2 \times 10^{-15} W$$ (100-200 K Tsys)

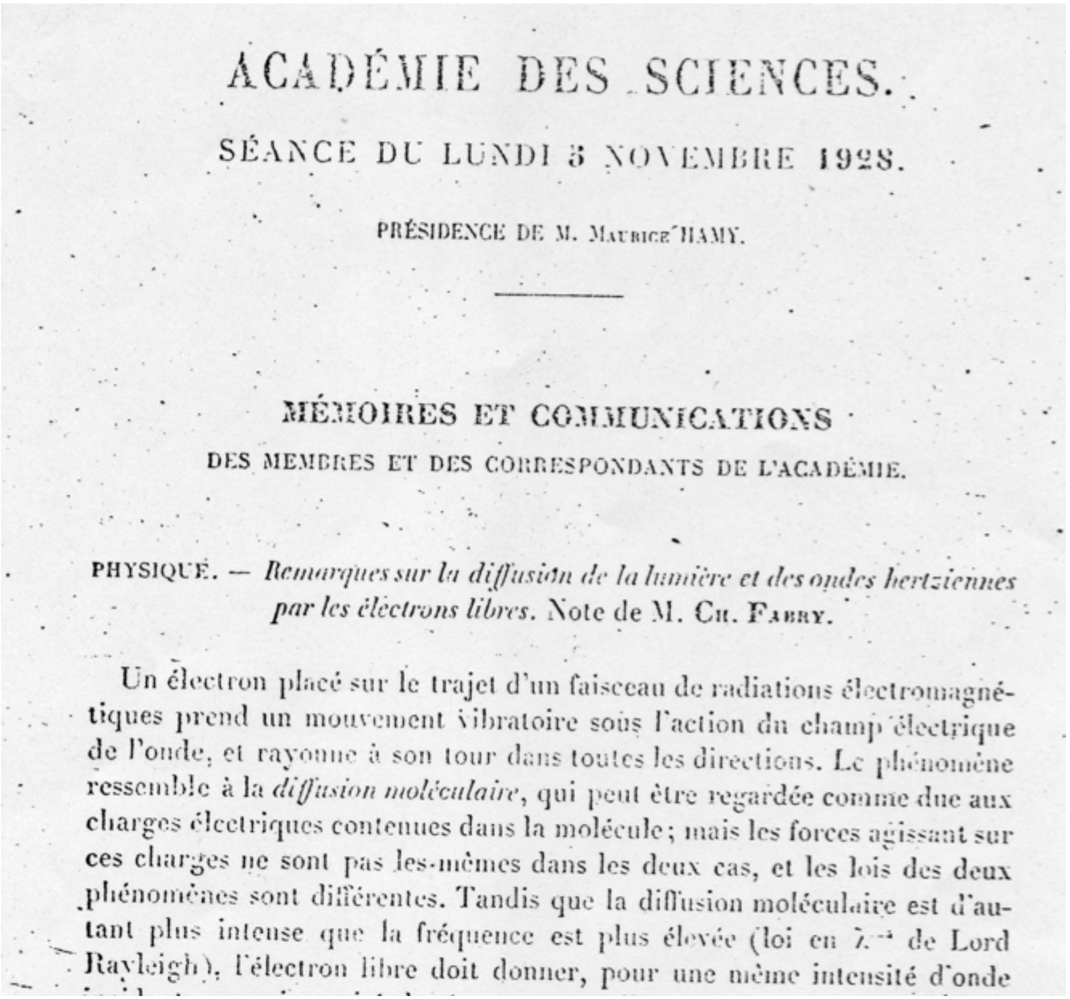
$$S/N \sim 5$$

Workable!

But you need a megawatt class transmitter and a huge antenna.

1950s: technology makes this possible (radio astronomy + construction = large antennas, military needs = high power transmitters)

Incoherent Scatter Concepts Are Older Than You Think


ACADÉMIE DES SCIENCES.

SÉANCE DU LUNDI 5 NOVEMBRE 1928.

PRÉSIDENCE DE M. MAURICE HAMY.

MÉMOIRES ET COMMUNICATIONS

DES MEMBRES ET DES CORRESPONDANTS DE L'ACADÉMIE.

PHYSIQUE. — *Remarques sur la diffusion de la lumière et des ondes hertziennes par les électrons libres.* Note de M. CH. FABRY.

Un électron placé sur le trajet d'un faisceau de radiations électromagnétiques prend un mouvement vibratoire sous l'action du champ électrique de l'onde, et rayonne à son tour dans toutes les directions. Le phénomène ressemble à la *diffusion moléculaire*, qui peut être regardée comme due aux charges électriques contenues dans la molécule; mais les forces agissant sur ces charges ne sont pas les mêmes dans les deux cas, et les lois des deux phénomènes sont différentes. Tandis que la diffusion moléculaire est d'autant plus intense que la fréquence est plus élevée (loi en λ^{-4} de Lord Rayleigh), l'électron libre doit donner, pour une même intensité d'onde

Remarques sur la diffusion de la lumière et des ondes hertziennes par les electrons libres

C. Fabry
1928

Charles Fabry
1867-1945

$$\sigma = \frac{8\pi}{3}\frac{e^4}{m^2}$$

Electron scattering cross section (fundamental)

First Incoherent Scatter Radar

- W. E. Gordon of Cornell is credited with the idea for ISR.
- *"Gordon (1958) has recently pointed out that scattering of radio waves from an ionized gas in thermal equilibrium may be detected by a powerful radar."* (Fejer, 1960)
- Gordon proposed the construction of the Arecibo Ionospheric Observatory for this very purpose (NOT for radio astronomy as the primary application)

~40 megawatt-acres

- 1000' Diameter Spherical Reflector
  - 62 dB Gain
- 430 MHz line feed 500' above dish
- Gregorian feed
- Steerable by moving feed.

Proceedings of the IRE, November 1958

Incoherent Scattering of Radio Waves by Free Electrons with Applications to Space Exploration by Radar*

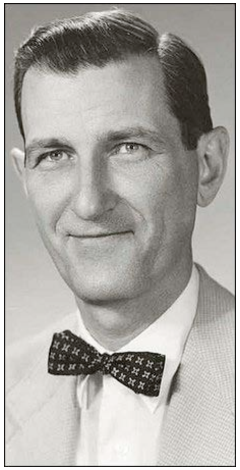
W. E. GORDON†, MEMBER, IRE

INTRODUCTION

FREE electrons in an ionized medium scatter radio waves incoherently so weakly that the power scattered has previously not been seriously considered. The calculations that follow show that this incoherent scattering, while weak, is detectable with a powerful radar. The radar, with components each representing the best of the present state of the art, is capable of:

1) measuring electron density and electron temperature as a function of height and time at all levels in the earth's ionosphere and to heights of one or more earth's radii;
2) measuring auroral ionization;
3) detecting transient streams of charged particles coming from outer space; and
4) exploring the existence of a ring current.

* Original manuscript received by the IRE, June 11, 1958; revised manuscript received, August 25, 1958. The research reported in this paper was sponsored by Wright Air Dev. Ctr., Wright-Patterson Air Force Base, O., under Contract No. AF 33(616)-5547 with Cornell Univ.
† School of Elec. Eng., Cornell Univ., Ithaca, N. Y.



First Incoherent-Scatter Radar

- **K.L. Bowles [Cornell PhD 1955]**, Observations of vertical incidence scatter from the ionosphere at 41 Mc/sec. *Physical Review Letters* 1958:

"*The possibility that incoherent scattering from electrons in the ionosphere, vibrating independently, might be observed by radar techniques has apparently been considered by many workers although seldom seriously because of the enormous sensitivity required…*"

First Incoherent-Scatter Radar

…*Gordon (*W.E. Gordon from Cornell*) recalled this possibility to the writer* [spring 1958; D. T. Farley] *while remarking that he hoped soon to have a radar sensitive enough to observe electron scatter in addition to various astronomical objects…"*

Bowles executed the idea - hooked up a large transmitter to a dipole antenna array in Long Branch Ill., took a few measurements.

Gordon presenting on same day at October 21, 1958 Penn State URSI meeting:

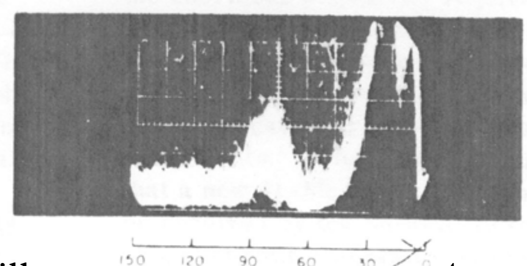
"…And then I want to tell you about a telephone call that I just had."

VOLUME 1, NUMBER 12 PHYSICAL REVIEW LETTERS DECEMBER 15, 1958

Table I. Parameters of radar equipment used.

Operating frequency	40.92 Mc/sec
Peak pulse power	(4 to 6) × 10^6 watts
Pulse duration	(50 to 150) × 10^{-6} sec
Average power	4 × 10^4 watts maximum
Receiver bandwidth	10, 15, or 30 kc/sec
Antenna cross section	116 × 140 meters (1024 half-wave elements in phase above ground)
Antenna polarization	north-south
Calculated antenna gain	~35 decibels/isotropic

~6 week setup time



Oscilloscope + camera + ~4 sec exposure (10 dB integration)

FIG. 2. Pulse width 50 μsec (~8 km), bandwidth 30 kc.

Incoherent Scattering Detectability

Bowles' results found approximately the expected amount of power scattered from the electrons (scattering is proportional to charge to mass ratio - electrons scatter the energy).

BUT: his detection with a 20 megawatt-acre system at 41 MHz (high cosmic noise background; should be marginal) implies a spectral width 100x narrower than expected – almost as if the much heavier (and slower) ions were controlling the scattering spectral width.

In fact, they do.

If this intrigues you..

ISR Summer Schools: Find Out More

2014 ISR Summer School

Arecibo Observatory

21-26 July 2014

Puerto Rico

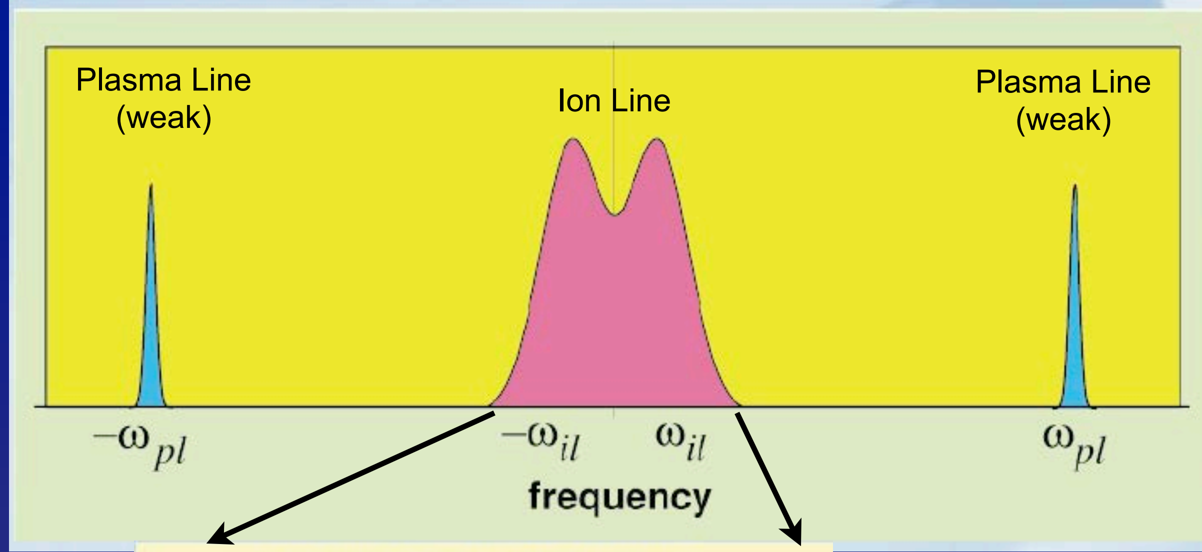
The 2014 ISR Summer School will be held at the Arecibo Observatory July 21 – July 26, inclusive. The school provides students with hands-on experience in designing and running experiments at incoherent scatter radar facilities. During this summer school, students will have the opportunity to run experiments with the Arecibo incoherent scatter radar (ISR) and use data from multiple ISR observatories, such as EISCAT, Poker Flat (PFISR), Millstone Hill, Resolute Bay (RISR), Sondrestrom, and Jicamarca. The school will be structured to provide presentations in the morning and hands-on experience in experiment design and analysis in the afternoons. The morning lectures will include an introduction to the theory of incoherent scatter, radar operations, ISR analysis techniques, and the Madrigal database. The afternoon exercises will involve working closely with ISR facility staff in the topic areas of: proposal design, experiment execution, and data analysis. All students will have the opportunity to work one-on-one with experienced scientists from multiple institutions.

The ISR summer school is suitable for graduate and advanced undergraduate students and attendance is limited. For most students attending institutions within the United States, travel, housing and meals will be provided. For post-docs and students outside of the United States, funding will be considered on a case-by-case basis. Students applying from EISCAT countries should visit here . Providing there is space, professors and other professionals are welcome to observe. Please email summerschool@esd.sri.com if you are interested in this option. All students who wish to apply for the ISR summer school must follow the application instructions:

IS Spectral Shape Demonstration

(IS Spectrum Java applet)

IS Radar Remote Sensing Capabilities



Parameters sensed:

Basic

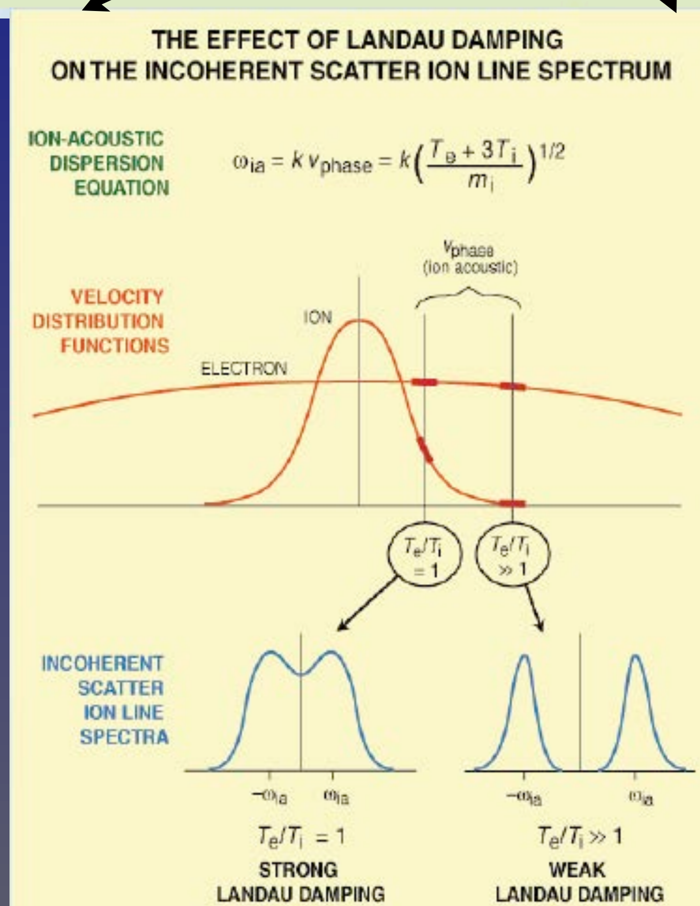
- Electron density
- Electron temperature
- Ion temperature
- Ion composition
- LOS Velocity

Derived

- Neutral winds
- Neutral temperature
- Vector velocity

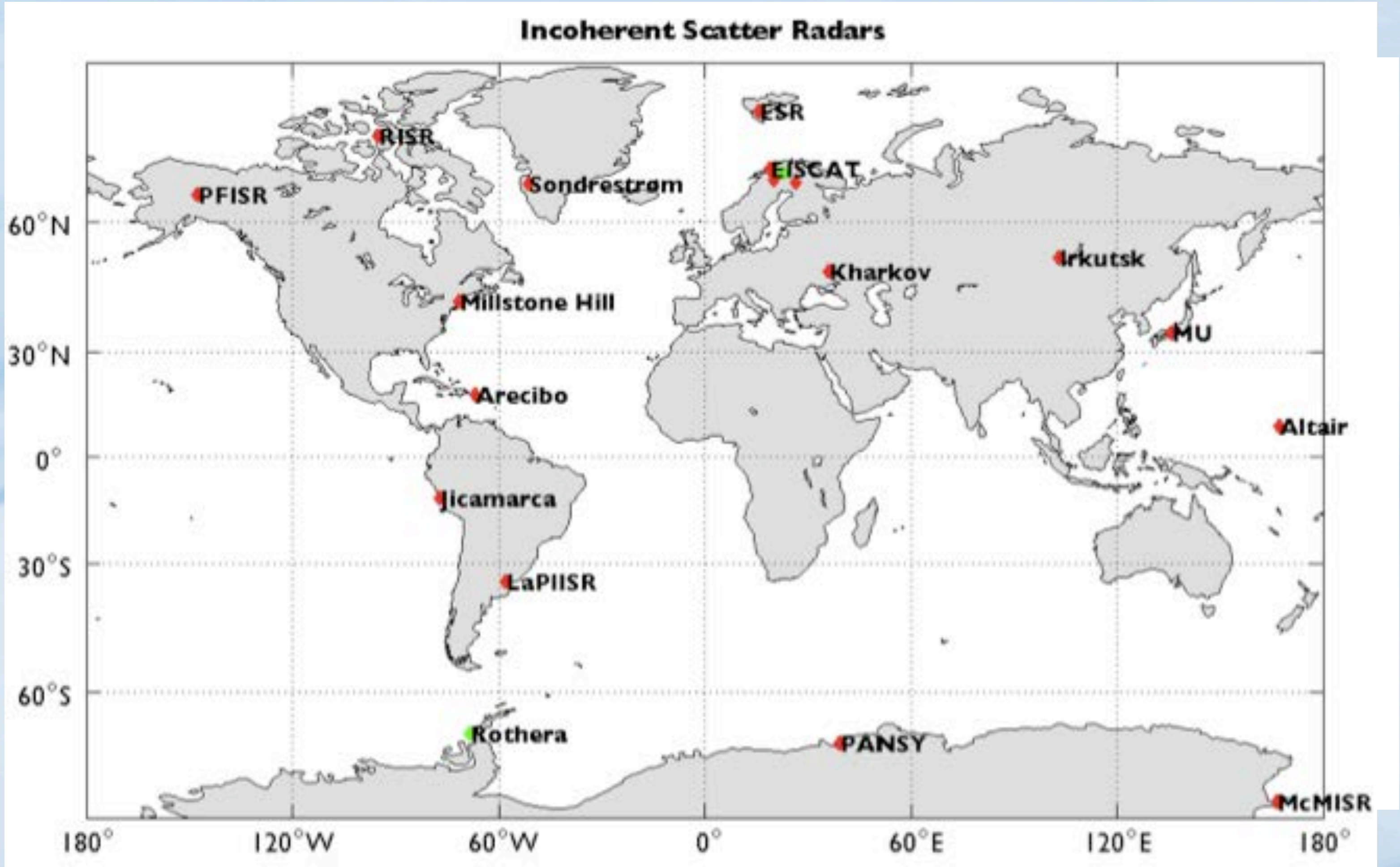
More limited

- Ion-neutral collisions (E region)
- Background mag field (equator)
- Unequal Ti (Arecibo)
- Faraday rotation (Jicamarca)
- Non-Maxwellian plasma
- Etc....



Example: "Ion Line" Sensitivity to Plasma Temperatures

Incoherent Scatter Radars of the World



NSF Geospace Facilities: IS Radar Chain

US National Science Foundation
Geospace Facilities
AGS Directorate

Millstone Hill Observatory:

Incoherent Scatter Radar (ISR):
440 MHz @ 2.5 MW Peak
68 m Zenith Antenna
46 m Steerable Antenna (MISA)

Wide Field of Coverage
Full Span of Mid-Latitude, Subauroral Processes

12 FTE Staff (16 Individuals)
Senior, Research,
Professional, Support
Undergrad, Grad Student Collaborations

Radar Operations: 1000 – 2000 hours per year of ionospheric observations
Primary support via NSF Geospace Facilities program
Many community PIs - fully flexible for special dedicated experiments
Coordinated International Observations (~750 hours per year)
Separately funded research projects : NASA, NRL, AFOSR, MIT Lincoln Lab
Typically less than 10% of nominal operating hours

Jicamarca Radio Observatory (Peru)

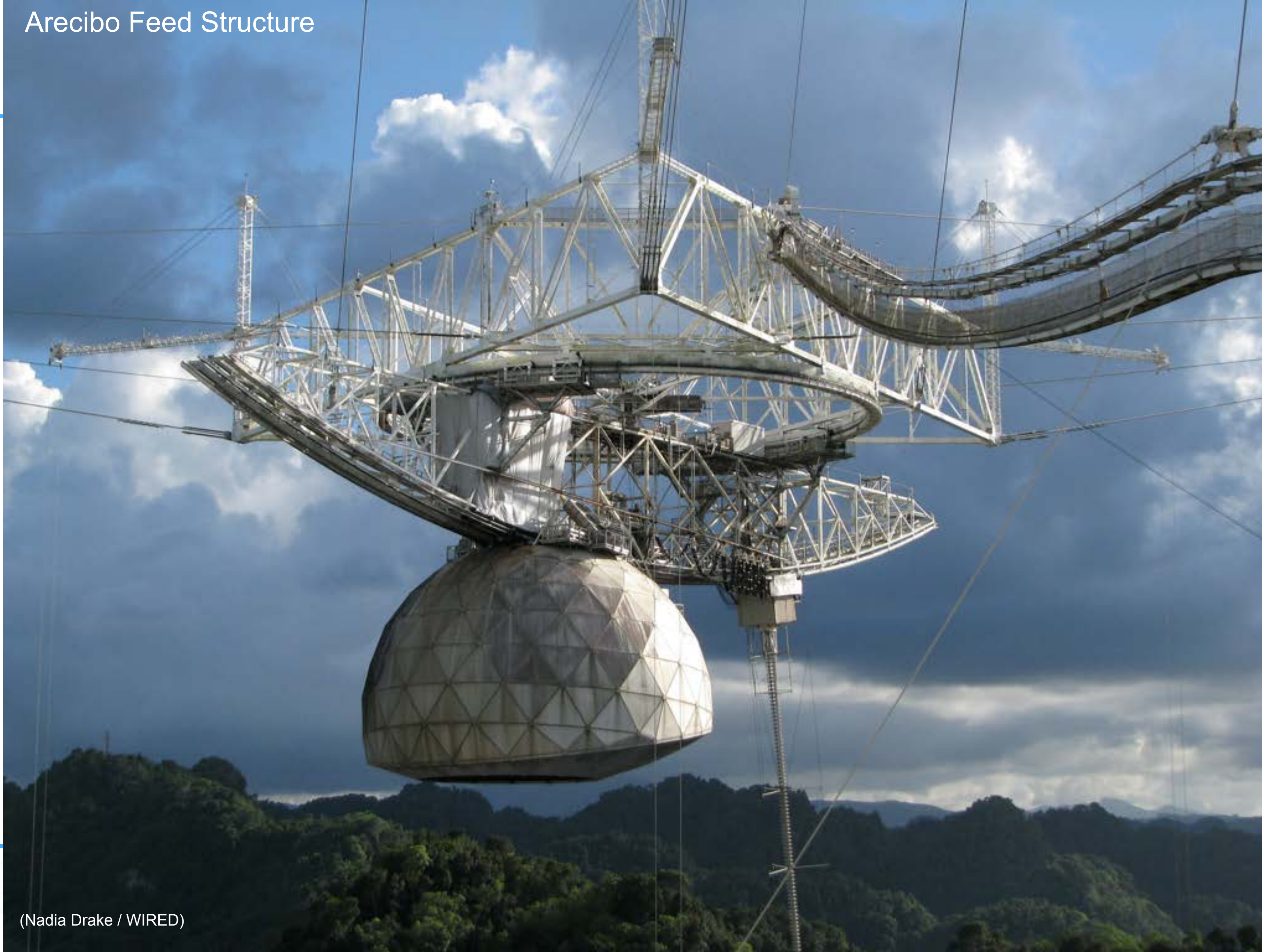
Arecibo Observatory (Puerto Rico)

IEEE 20th Century Milestone

Dedicated 1964

300 m Reflector

Arecibo Feed Structure



(Nadia Drake / WIRED)

Millstone Hill Observatory (Westford, MA)

68 meter zenith antenna

46 meter steerable antenna

2.5 MW UHF transmitter

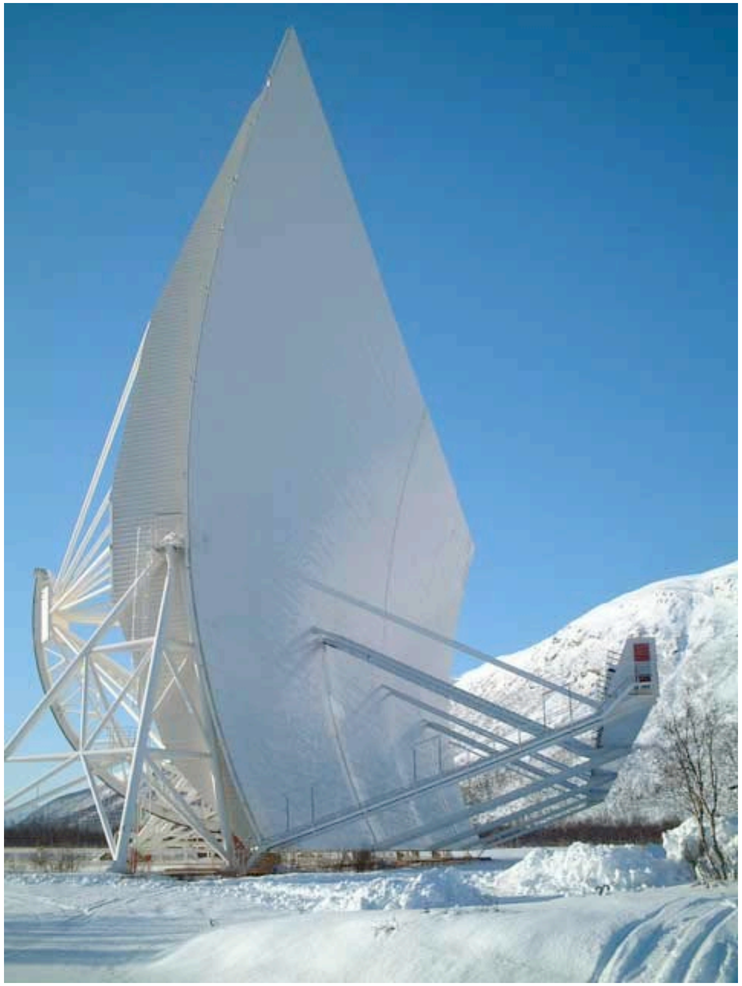
Operational since 1960

Sondrestrom ISR (Kellyville, Greenland)

32 meter antenna

2.5 MW L band transmitter

EISCAT Mainland



Tromsø, Norway
Kiruna, Sweden
Sødankyla, Finland

UHF, VHF

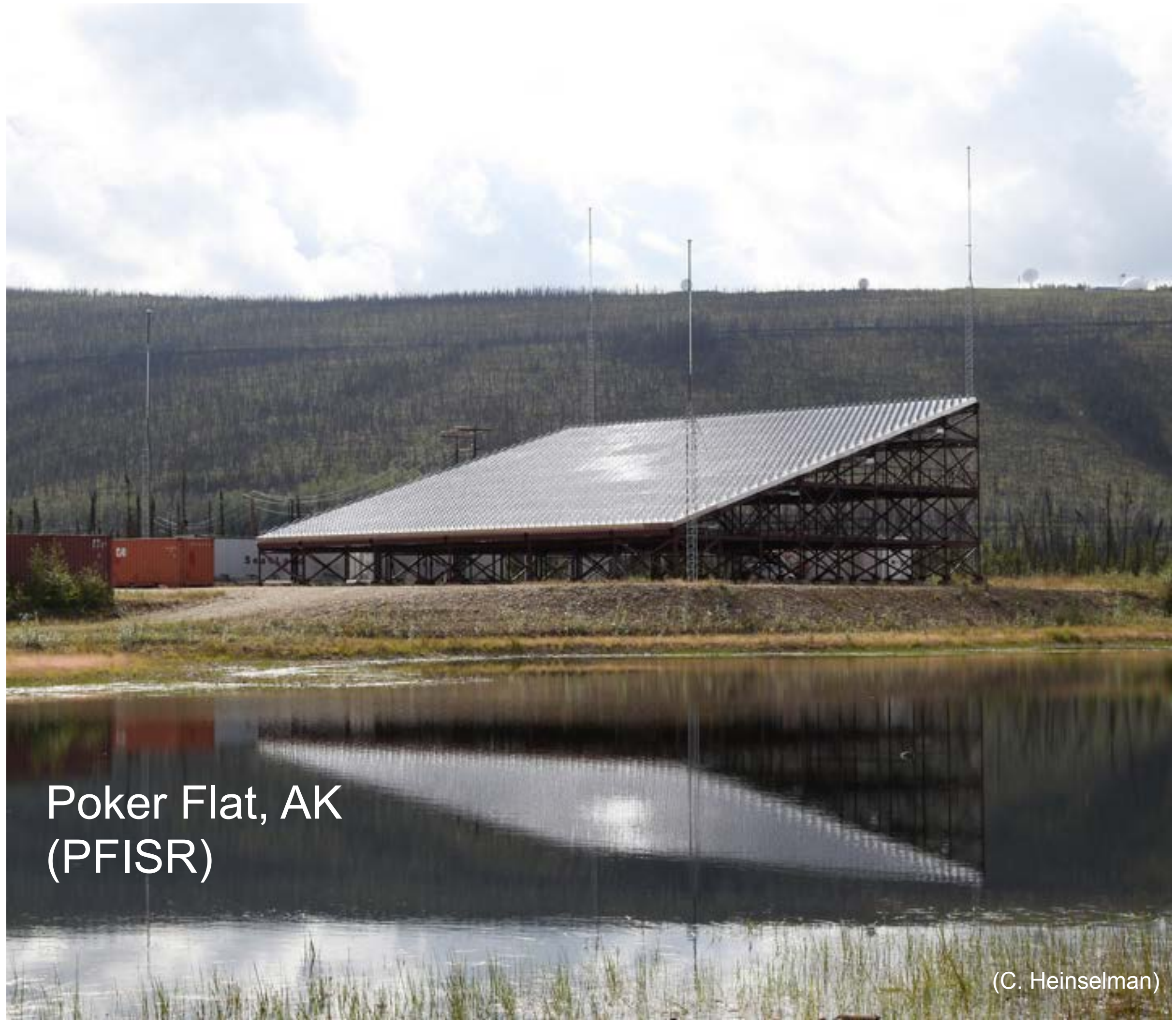
Advanced Modular Incoherent Scatter Radar (AMISR)

4096 element phased array

Electronically steered

2 MW effective peak power

449 MHz UHF frequency



Advanced Modular Incoherent Scatter Radar (AMISR)

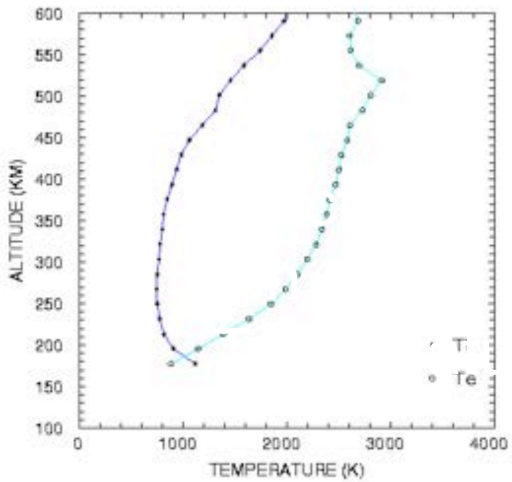
4096 element phased array

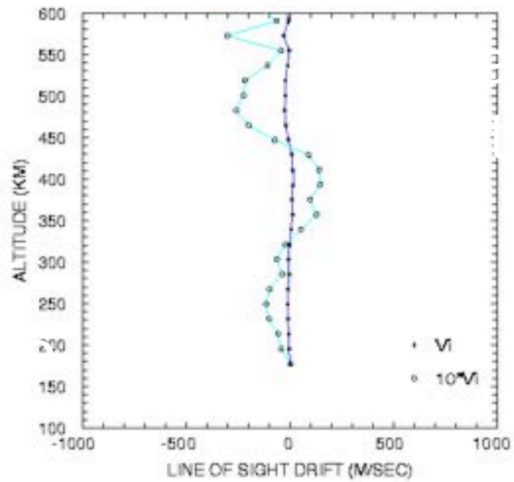
2 MW effective peak power

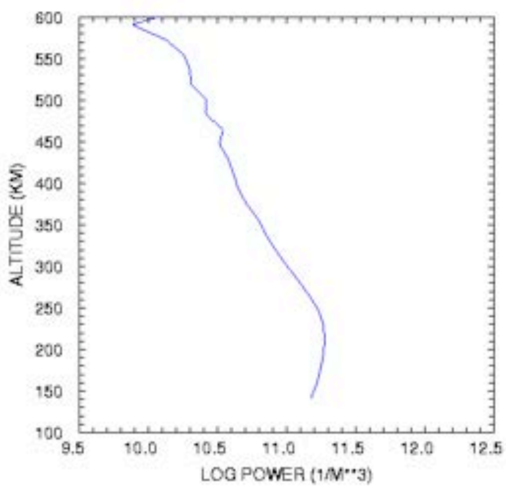
449 MHz UHF frequency

EISCAT 3D

Ionospheric Vertical Profiles

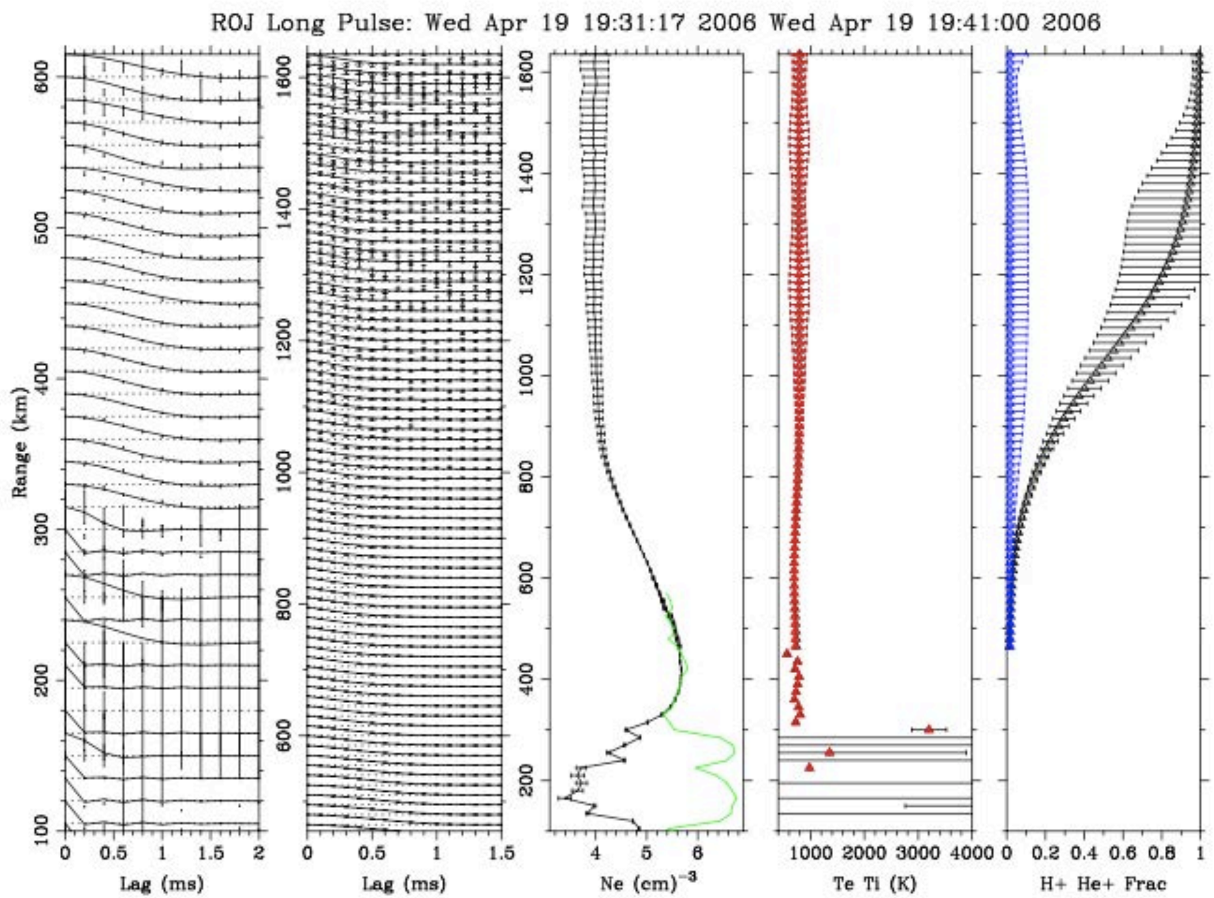






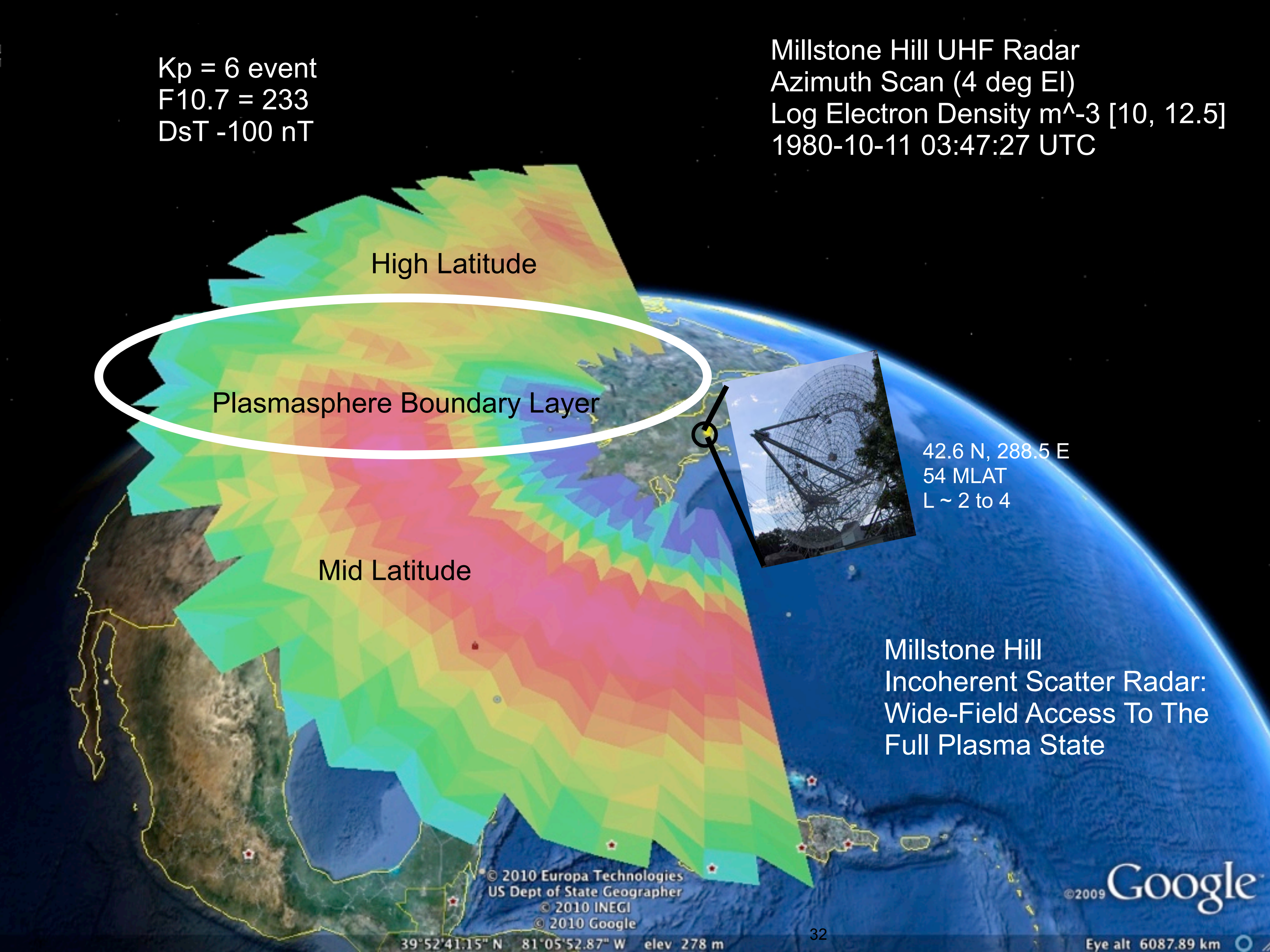
Millstone Hill
Zenith pointing
Daytime
2 minute integration

Equatorial Ionospheric Profiles: E, F Region, Topside

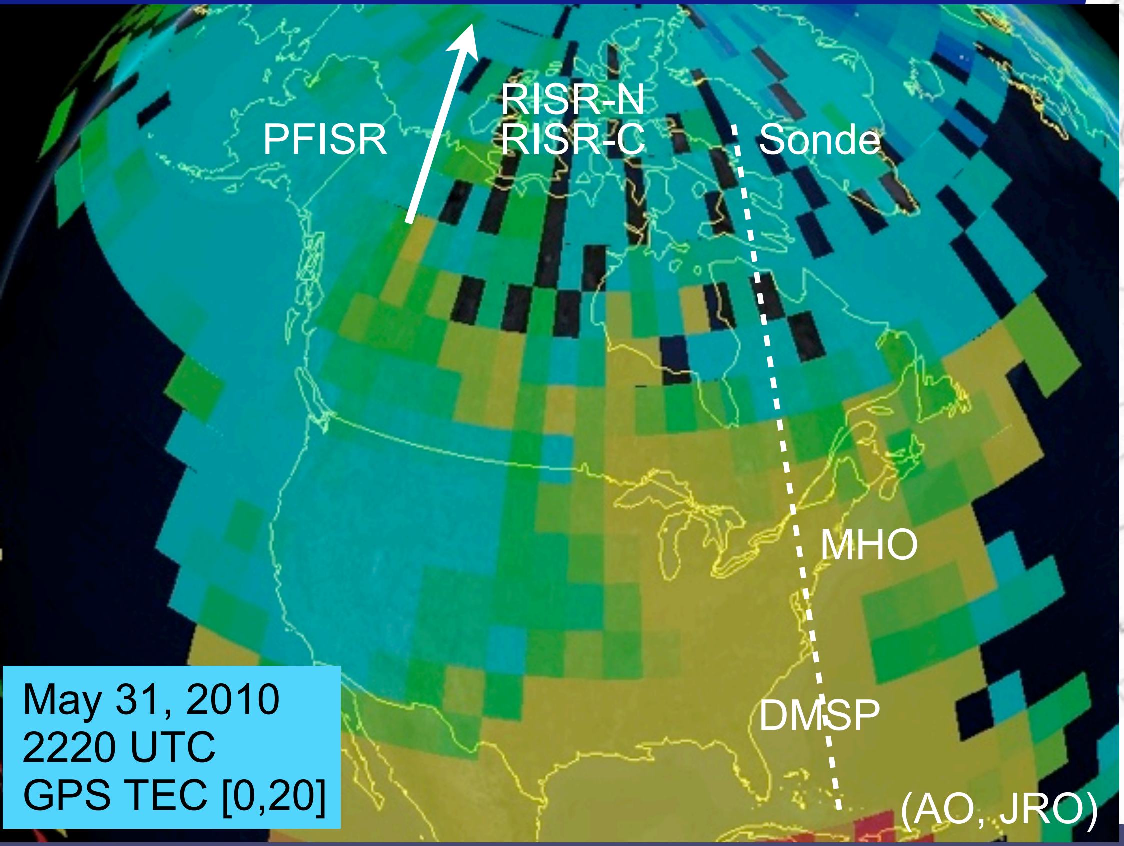


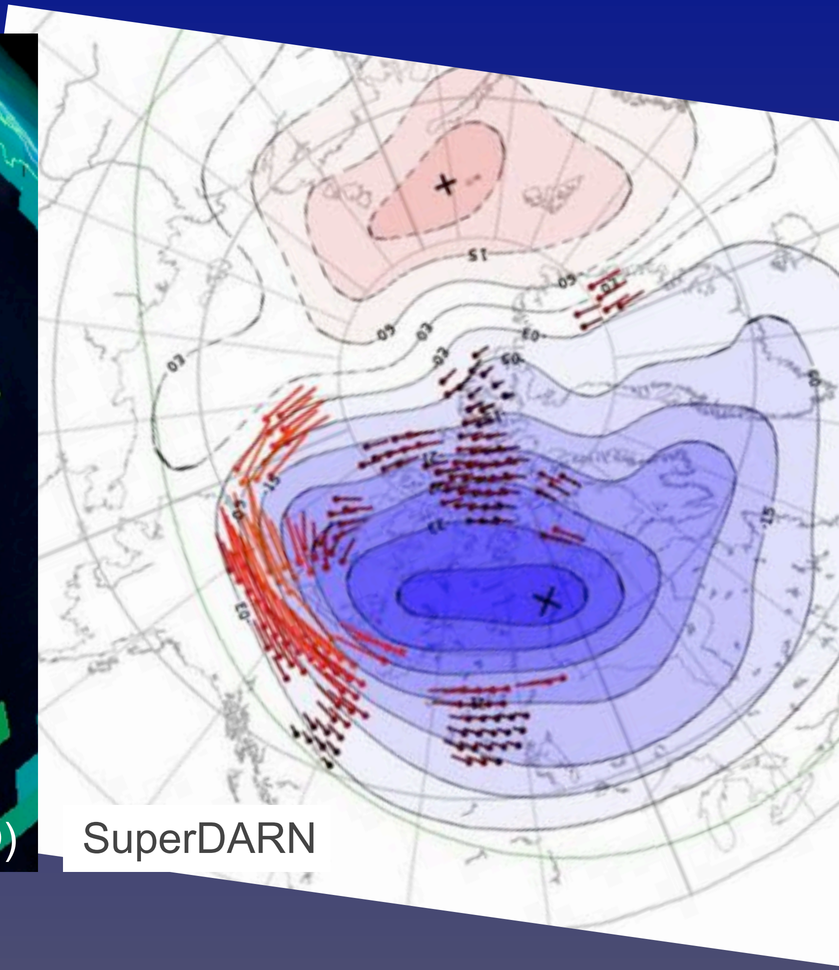
(Hysell et al, 2008)

Fig. 3. Jicamarca profiles for 19:30 LT (00:30 UT). From left to right, the panels represent double-pulse lag products, long-pulse lag products, electron density, electron and ion temperature, and light ion fraction (see text).


Kp = 6 event
F10.7 = 233
DsT -100 nT
Millstone Hill UHF Radar
Azimuth Scan (4 deg El)
Log Electron Density m^-3 [10, 12.5]
1980-10-11 03:47:27 UTC
High Latitude
Plasmasphere Boundary Layer
Mid Latitude
42.6 N, 288.5 E
54 MLAT
L ~ 2 to 4
Millstone Hill
Incoherent Scatter Radar:
Wide-Field Access To The
Full Plasma State
© 2010 Europa Technologies
US Dept of State Geographer
© 2010 INEGI
© 2010 Google
©2009 Google
39°52'41.15" N 81°05'52.87" W elev 278 m
Eye alt 6087.89 km

American Sector ISR Coverage During DMSP Overflight [840 km]





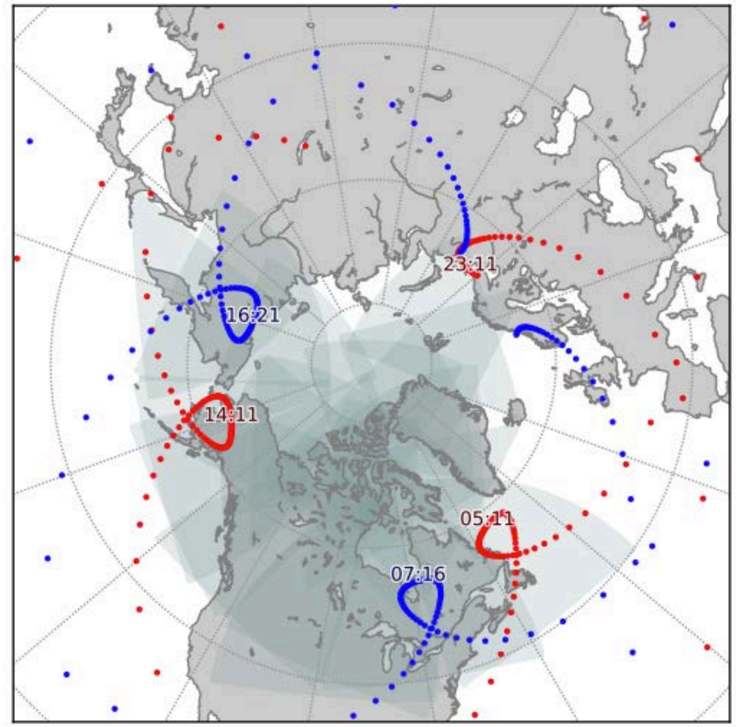
System Level Responses Require System Level Observations and Science
(A Philosophy At The Heart of CEDAR)

Ground track of s/c -A, -B
with Millstone Hill,
Mid-latitude SuperDARN network
plus GPS TEC

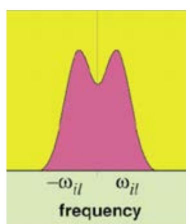
2013-02-02
0500 - 0600 UTC

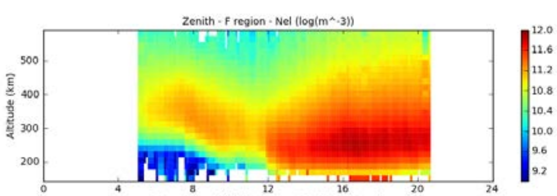
Part of a regularly scheduled
Van Allen Probes conjunction experiment

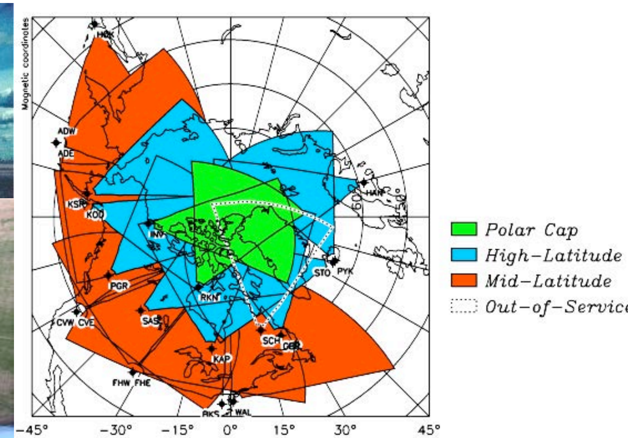
2013 - Feb - 02



VAP-A VAP-B (Virginia Tech)







Whole Atmosphere Coupling

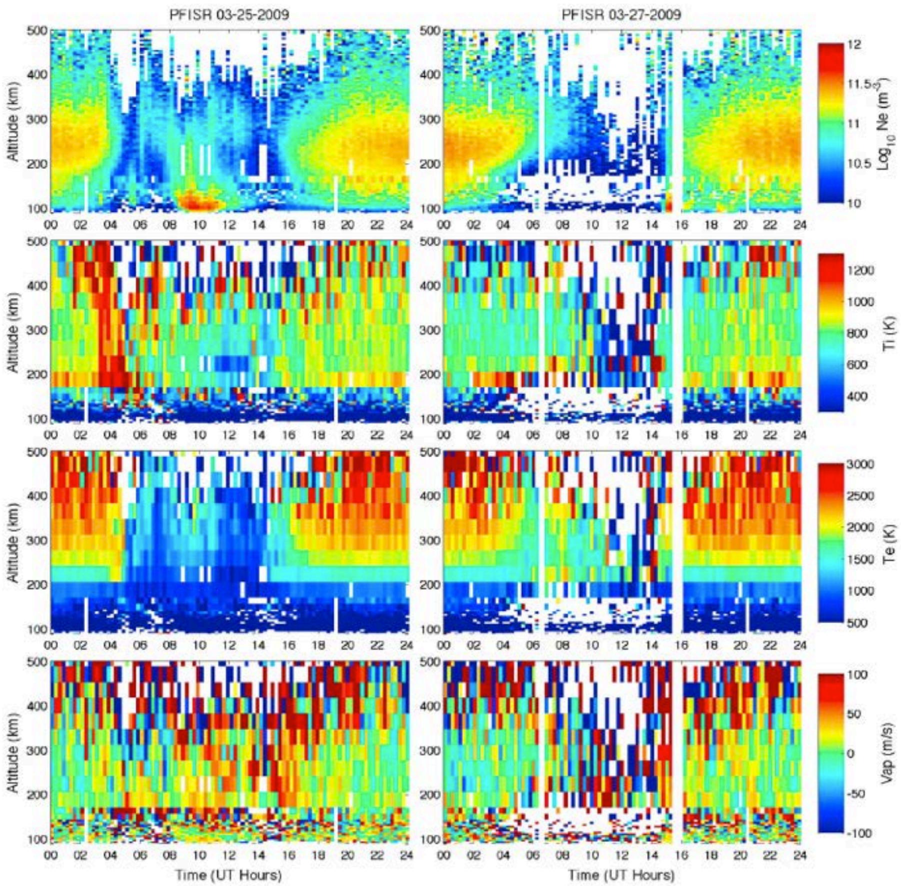


Figure 5. Ionospheric parameters for two 24 h periods on (left) 25 March and (right) 27 March. From top to bottom: electron density, ion temperature, electron temperature, and line of sight drift speed.

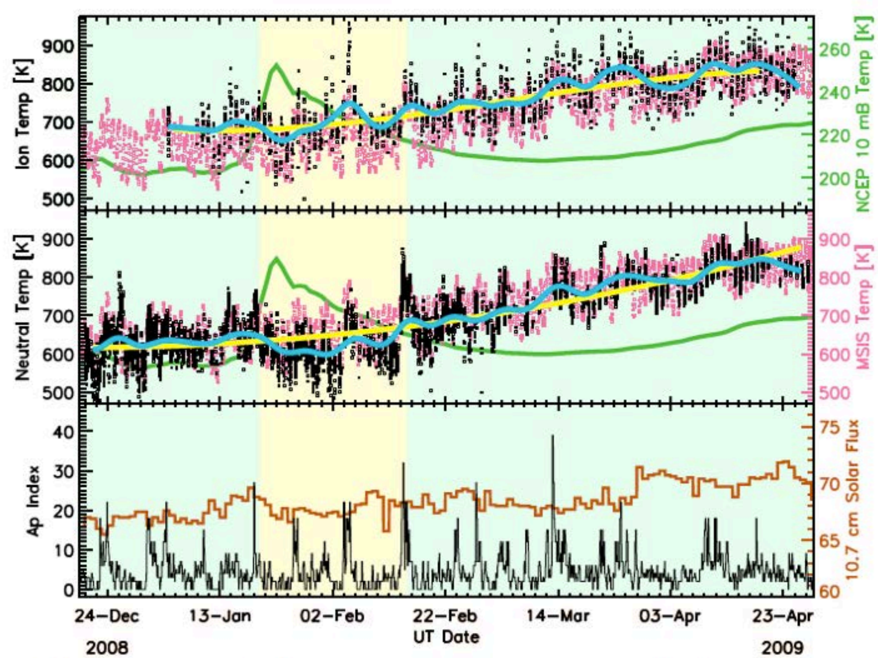
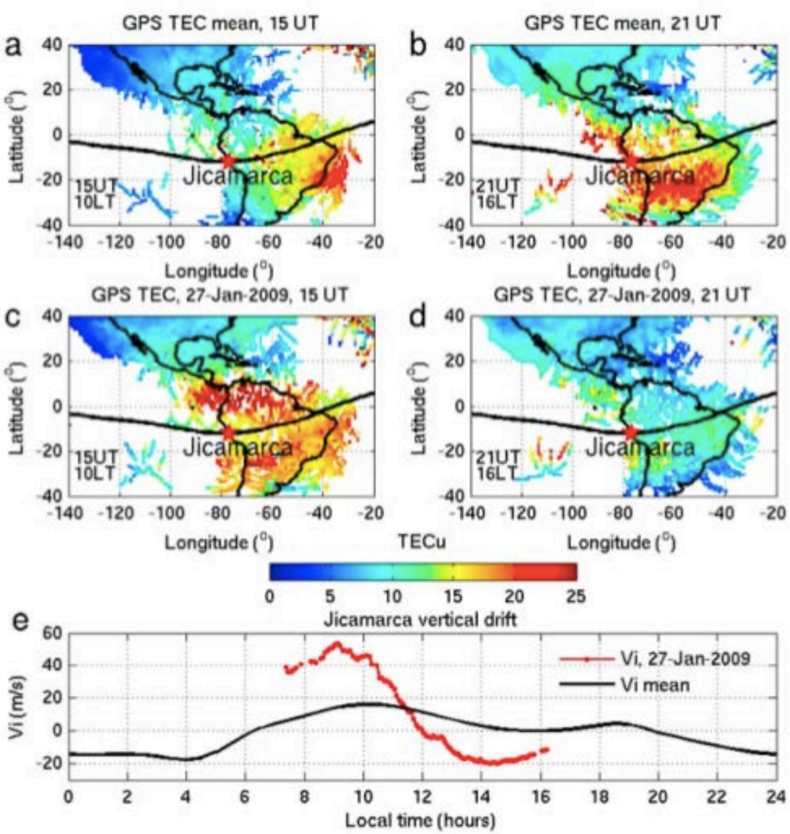


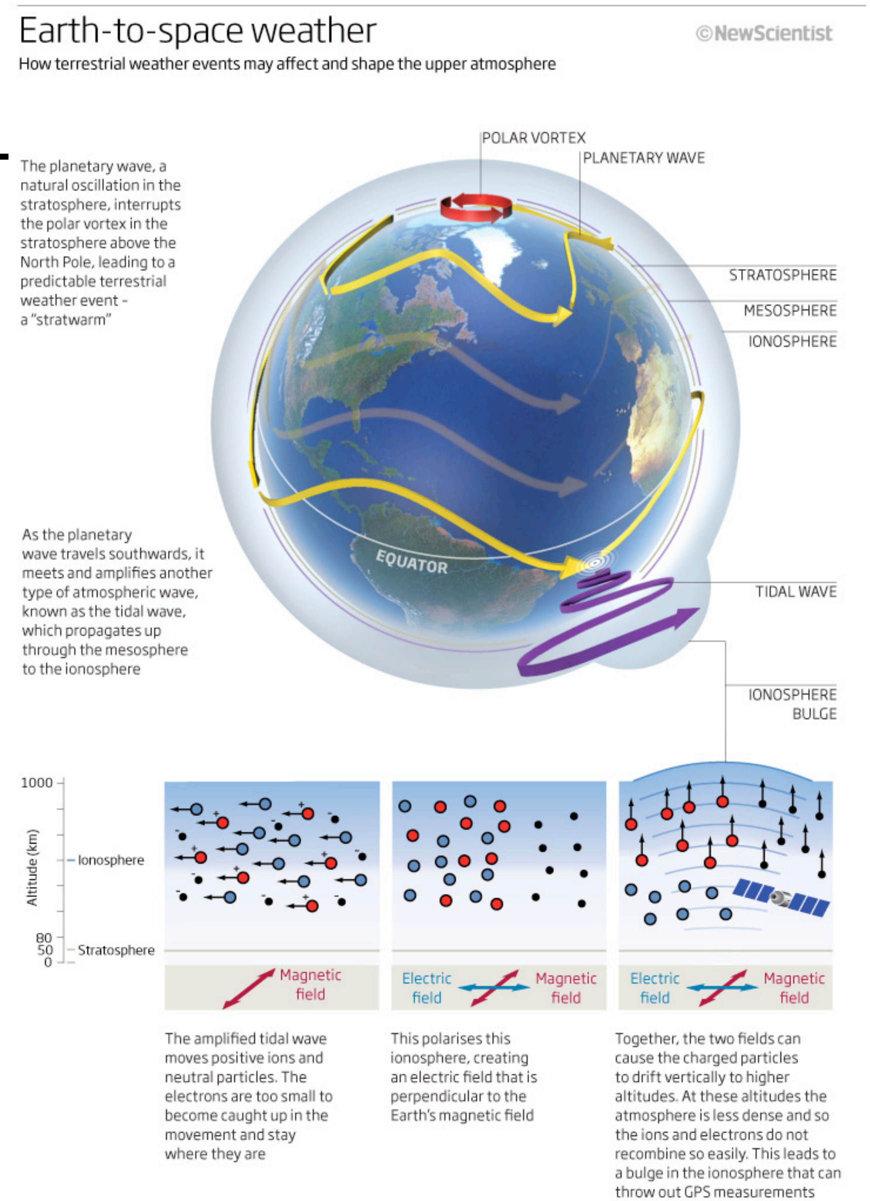
Figure 6. (top) Ion and (middle) neutral temperature observations for the whole study period, overlaid onto temperature estimates from the MSIS model evaluated hourly using (bottom) the appropriate A_p and $F_{10.7}$ values at each time. Green curves depict NCEP temperatures on the 10 hPa isobaric surface above Poker Flat. Blue curves in Figure 6 (top and middle) depict smoothed trends through the ion and neutral data, whereas yellow curves depict cubic polynomial fits to these data. A change in background shading (from blue to yellow) is used to highlight the period of stratospheric warming.

(Conde and Nicolls, 2010)

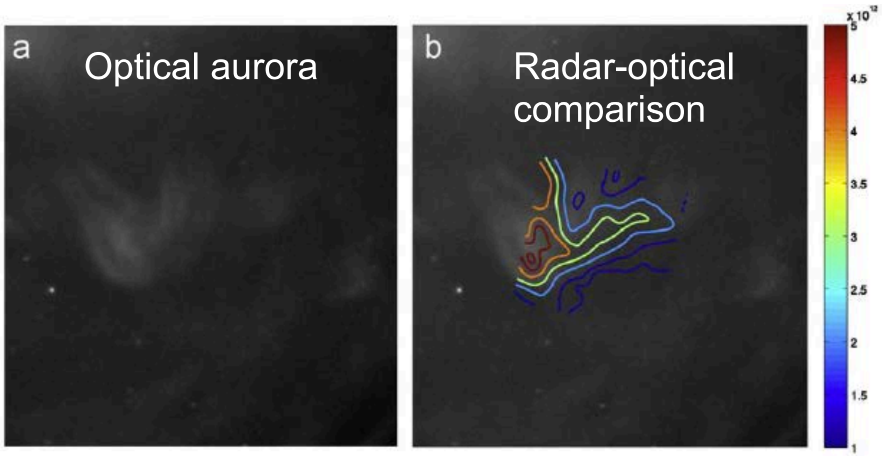
Whole Atmosphere Coupling

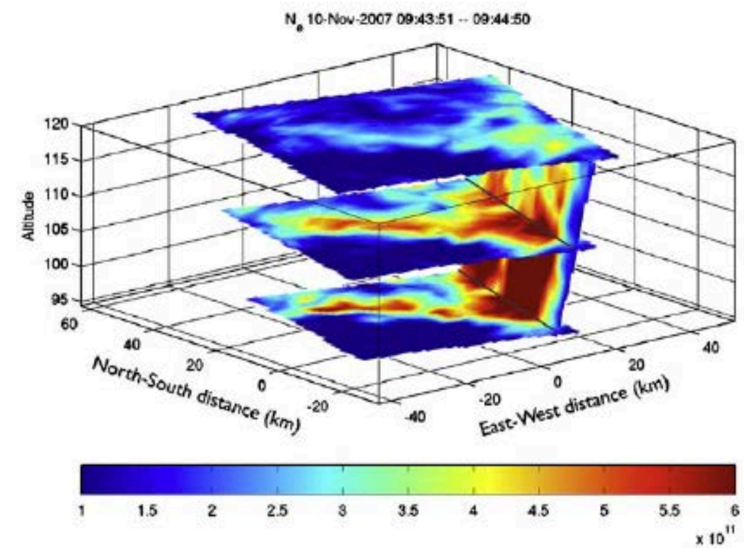


(Goncharenko et al, 2010)



3D Volumetric Ionospheric Measurements





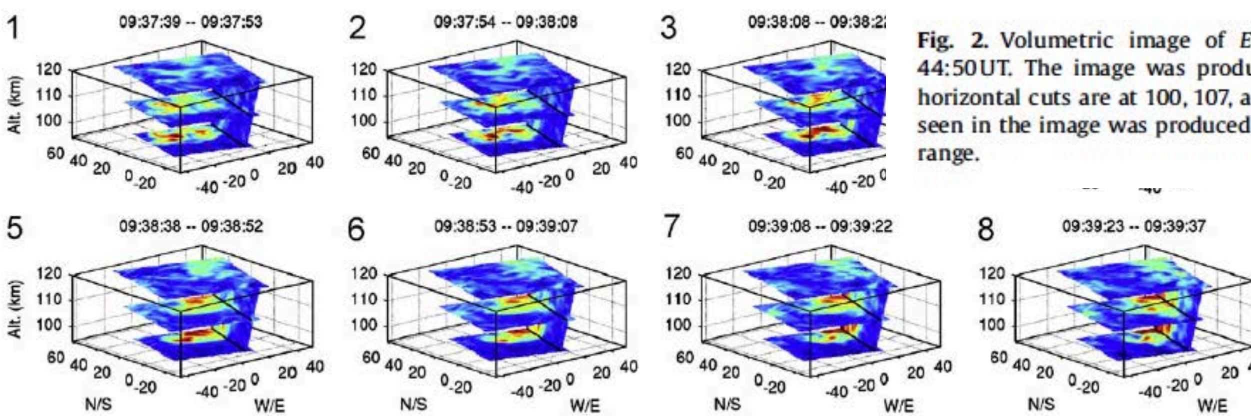


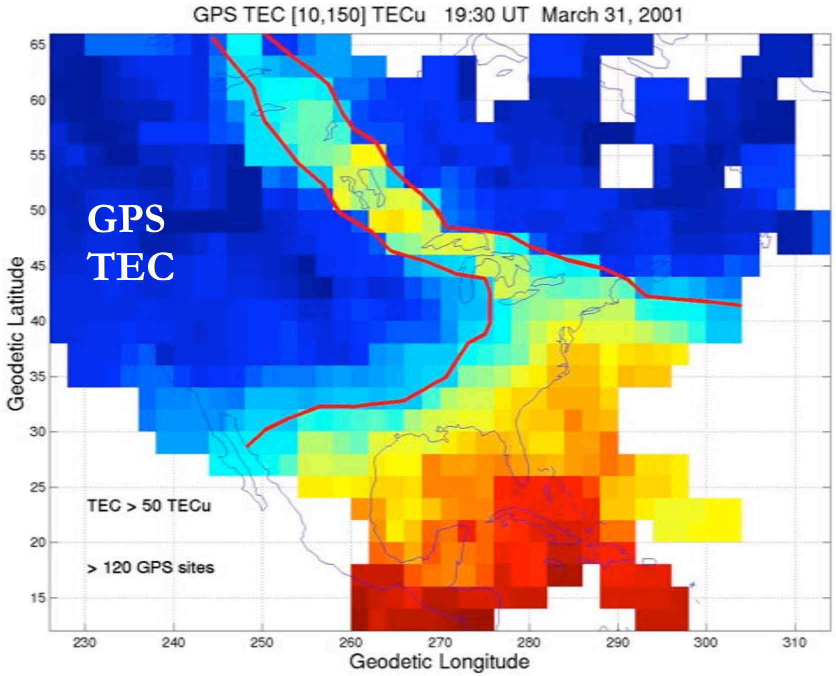
Fig. 2. Volumetric image of *E*-region on 10 November 2007, 09:43:51–09:44:50 UT. The image was produced by averaging 192 pulses-per-position. The horizontal cuts are at 100, 107, and 120 km. The structured density enhancement seen in the image was produced by auroral electron precipitation in the ~20 keV range.

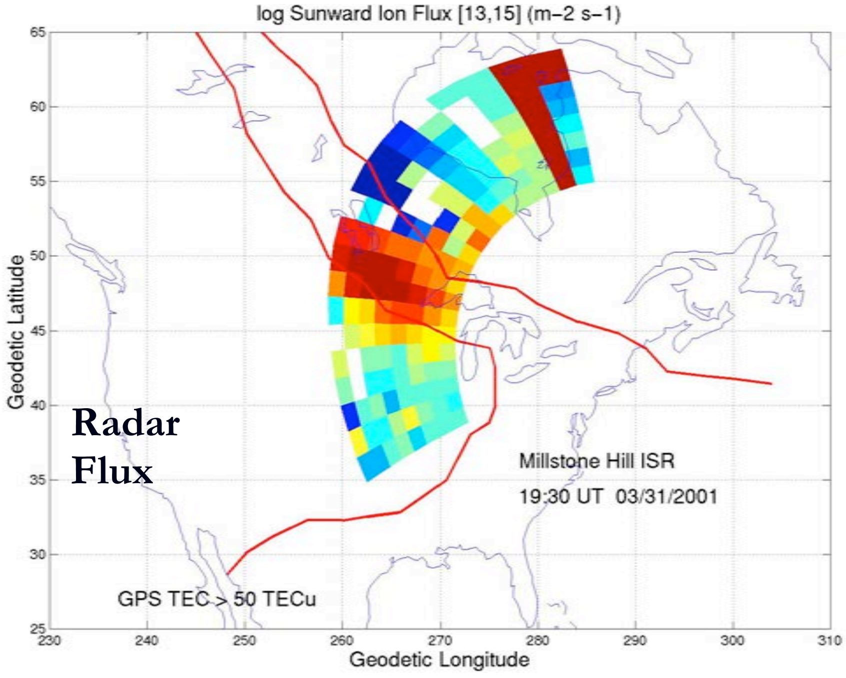
(Semeter et al 2009)

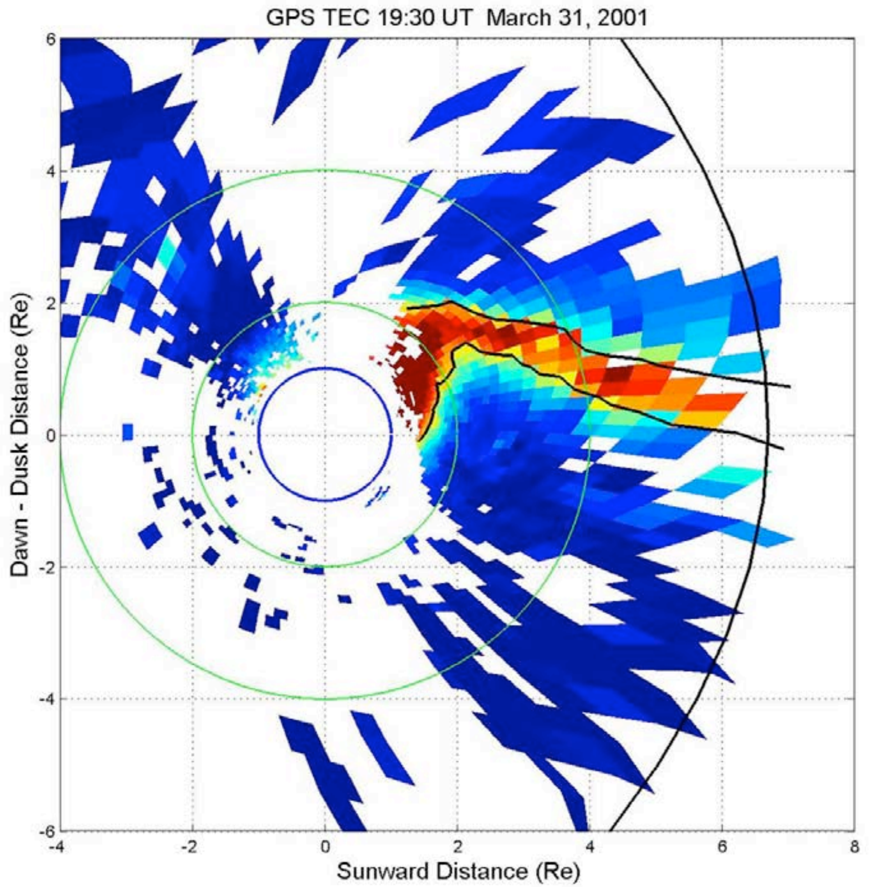
Fig. 7. Another interval at 14.6-s cadence (09:37:39–09:39:37 UT), showing a structure 'moving' from west to east in successive frames at ~100-km (same color scale as Fig. 2).

Plasma Redistribution TEC/ Plasmasphere Plume March 31, 2001

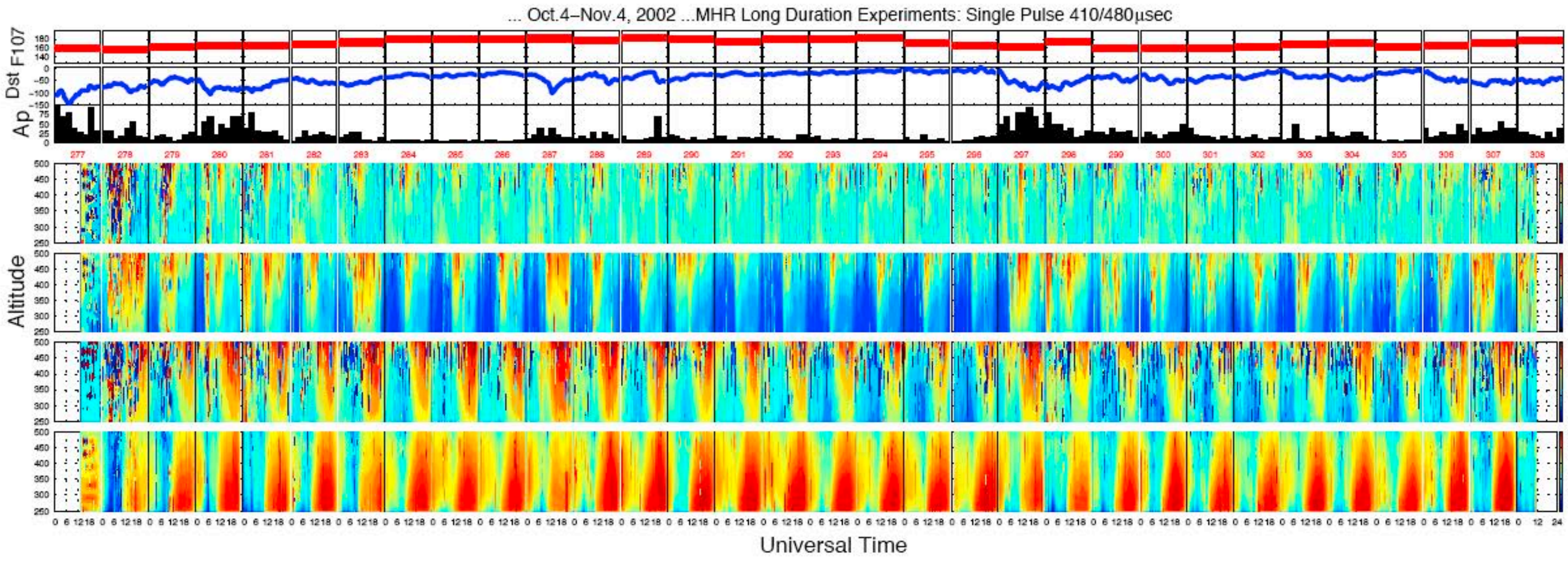
Magnetosphere-Ionosphere Coupling







Long-Term Ionospheric Observations



Community data sets for ionospheric variability

Excellent source of long term climate trend data

Easy Data Access: Madrigal/CEDAR System

- Upper atmospheric science database
- Distributed, web-based
- Multiple data types [radar, optical, etc.]
- CEDAR database format
- Data locally controlled
- Shared inter-site metadata
- Derived parameters [e.g. Mag field]
- Global search
- Full programming interface
- Open source development [www.openmadrigal.org]
- Site support for Madrigal nodes
- Hosting of community data sets

Summary

Incoherent Scatter Radar: the most powerful ground based technique for remotely sensing Earth's geospace plasma environment

Come do some science with us!

For more details:

`pje@haystack.mit.edu`

Facility staff are available to the entire community for collaborations, experiments, data reduction, interpretation