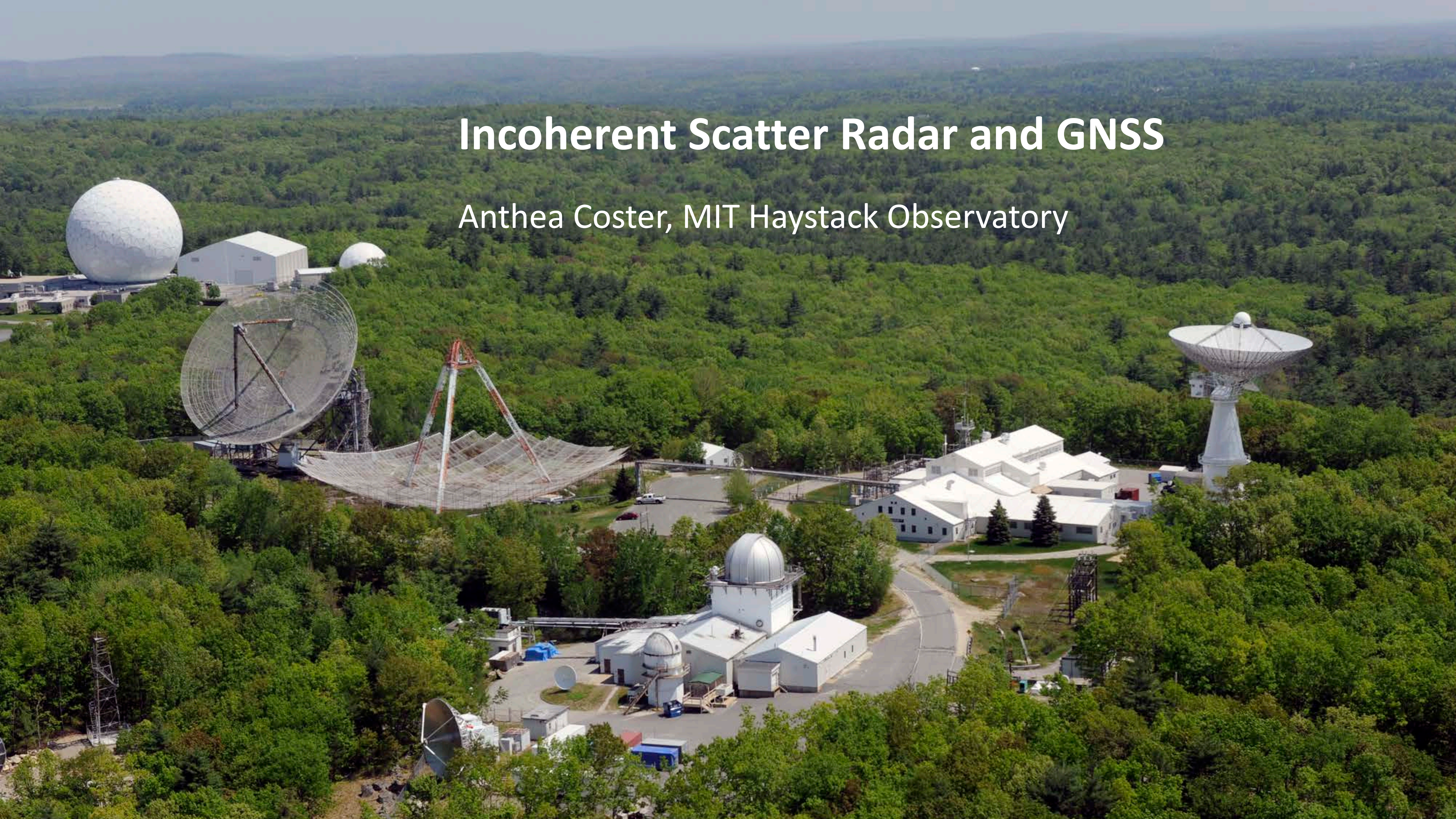
Incoherent Scatter Radar and GNSS

Anthea Coster, MIT Haystack Observatory



Outline

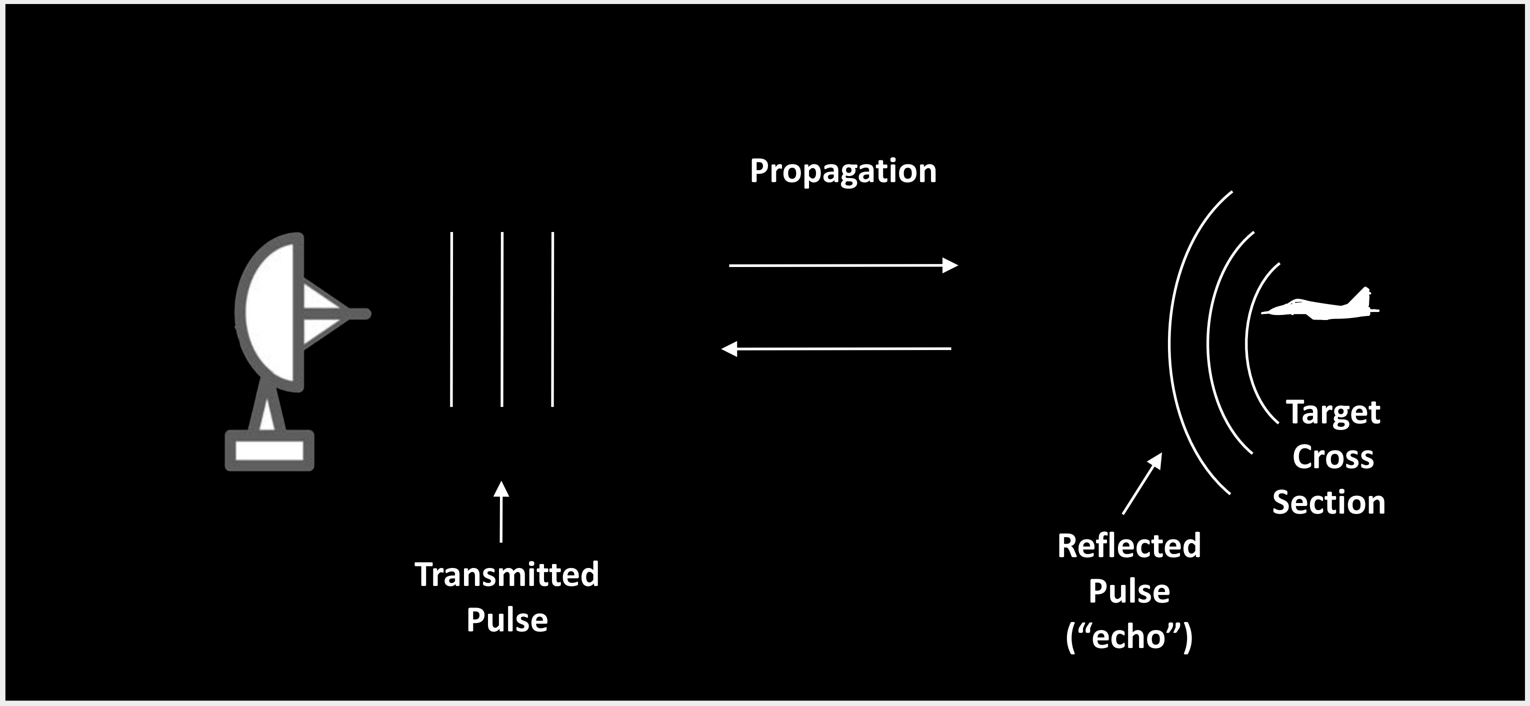
- This is an introduction to *two different methods* of measuring ionospheric properties.
  - Incoherent Radars – where the NSF radars are and what they measure
  - GNSS – the ground-based network and how it works as a unit
  - Madrigal Database – where to access the data

RADAR: RAdio Detection And Ranging

Radar observables:

- Target angles (azimuth & elevation)
- Target range
- Target size (radar cross section)
- Target speed (Doppler)
- Target features (imaging)

Return signal ≈ R^{-4}



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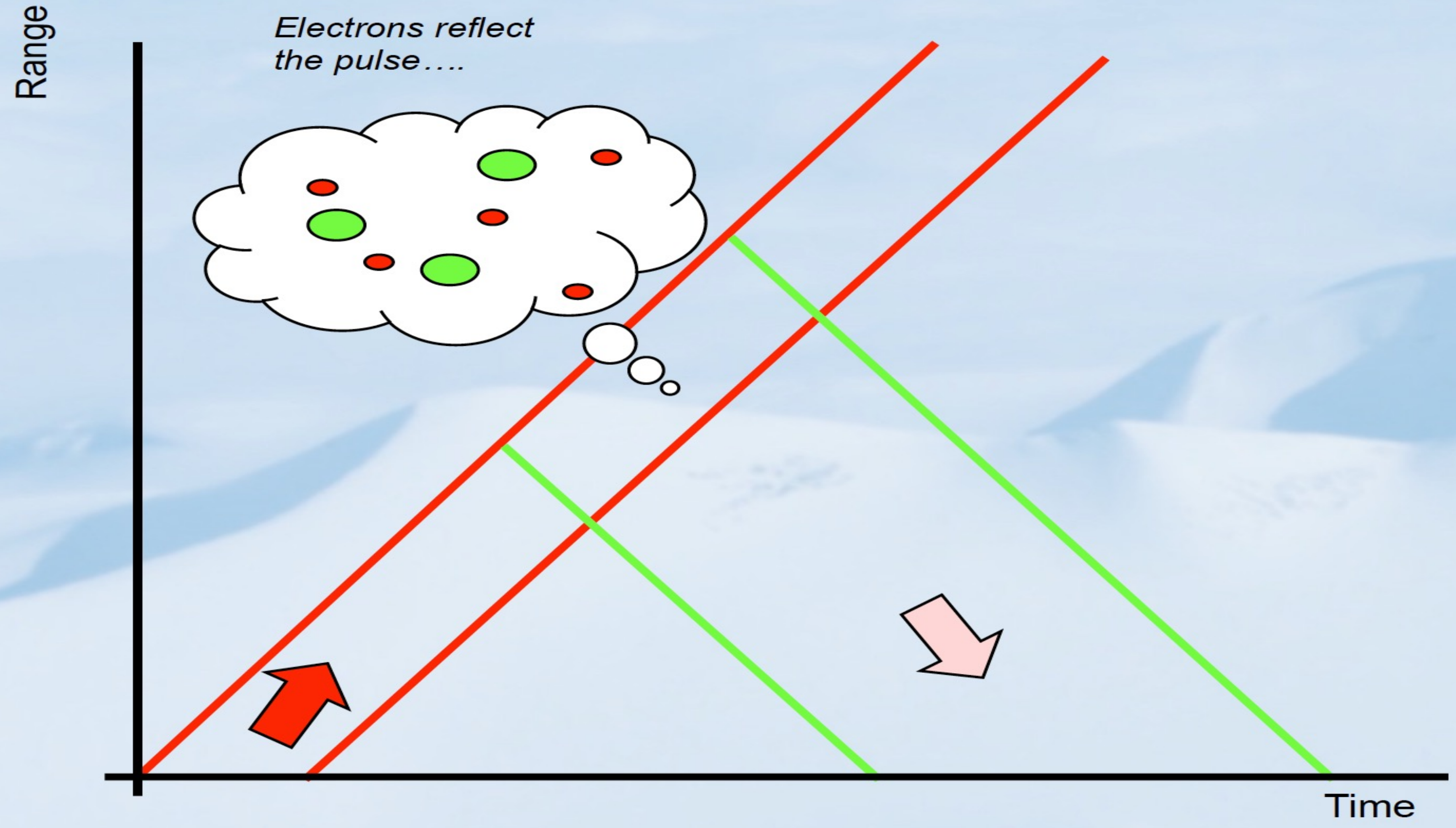
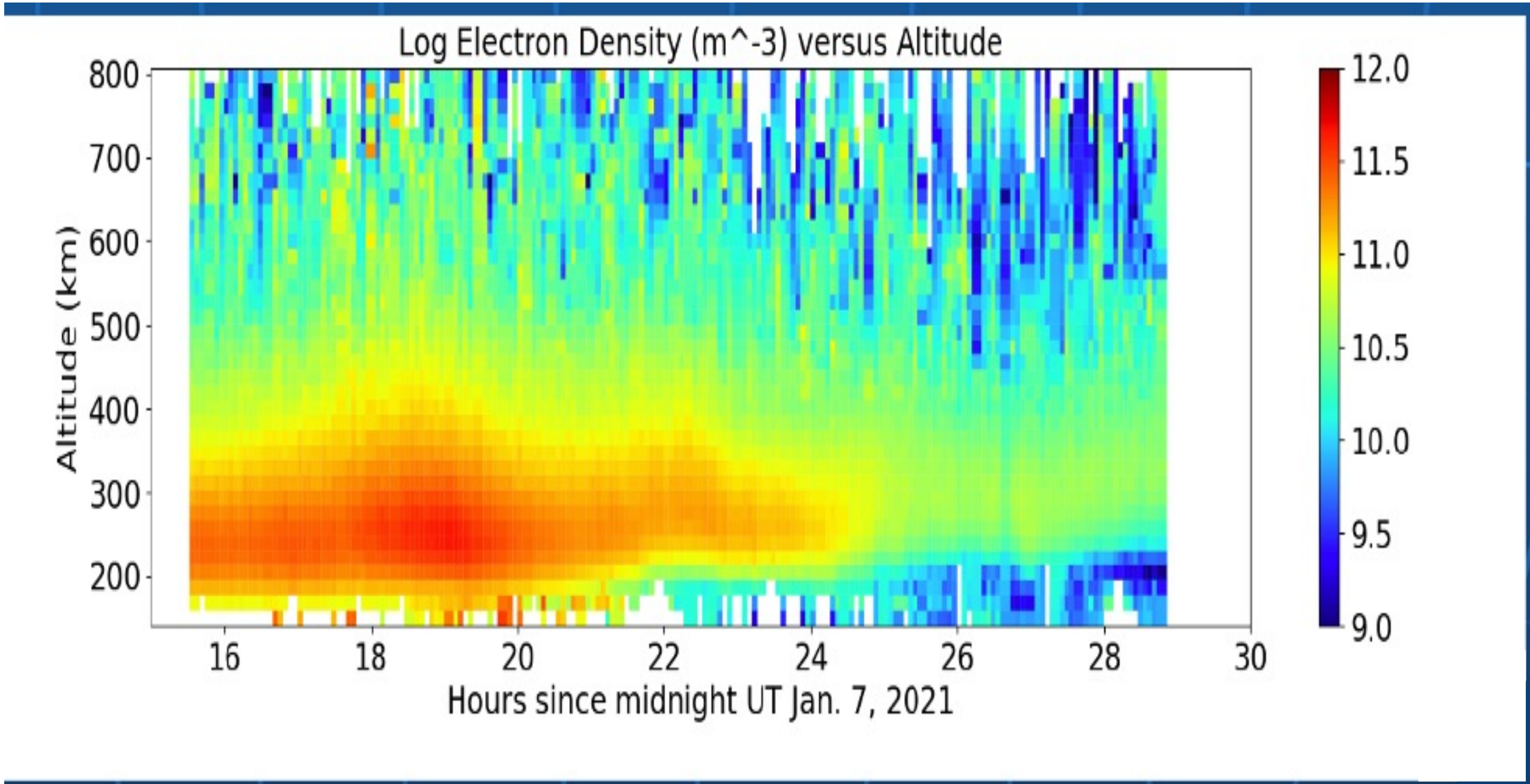
How ISRs work…



High power pulse

Very sensitive receiver

Only ~0.0000000000000000001% of the transmitted power is returned!



Typical ISR plot

IS Radar Remote Sensing Capabilities

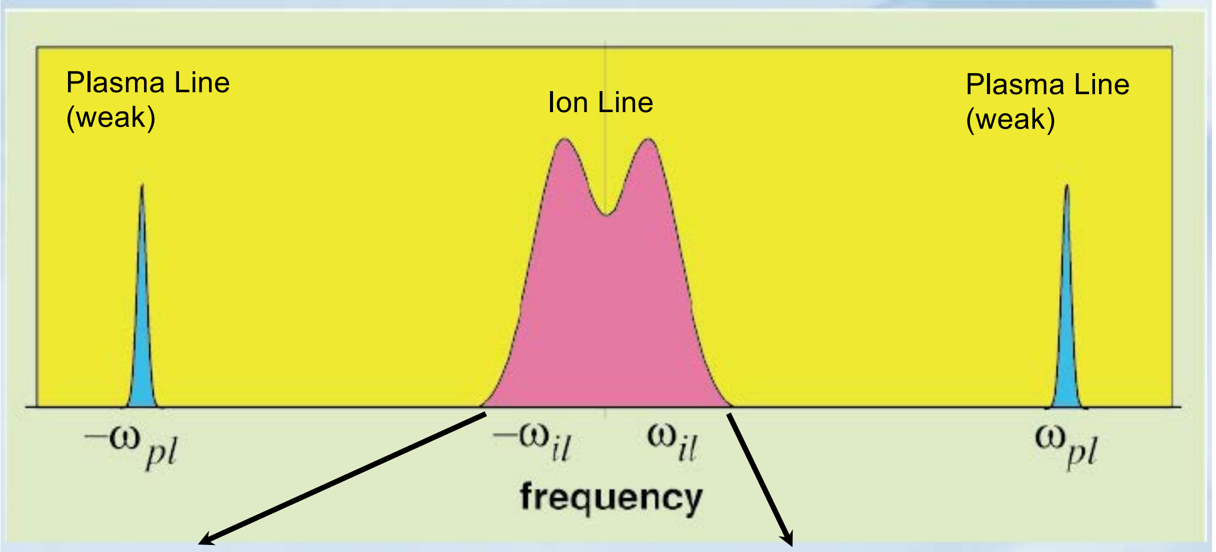
Suggest taking the ISR summer school

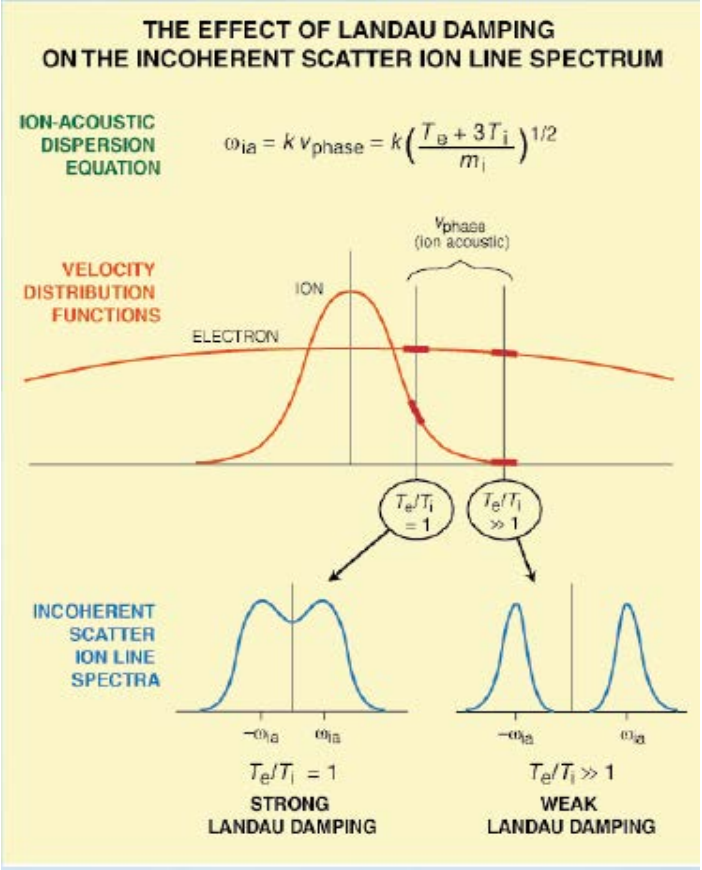
Parameters sensed:

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)
- Regularized binned/gridded data
- Etc....





Example: "Ion Line" Sensitivity to Plasma Temperatures

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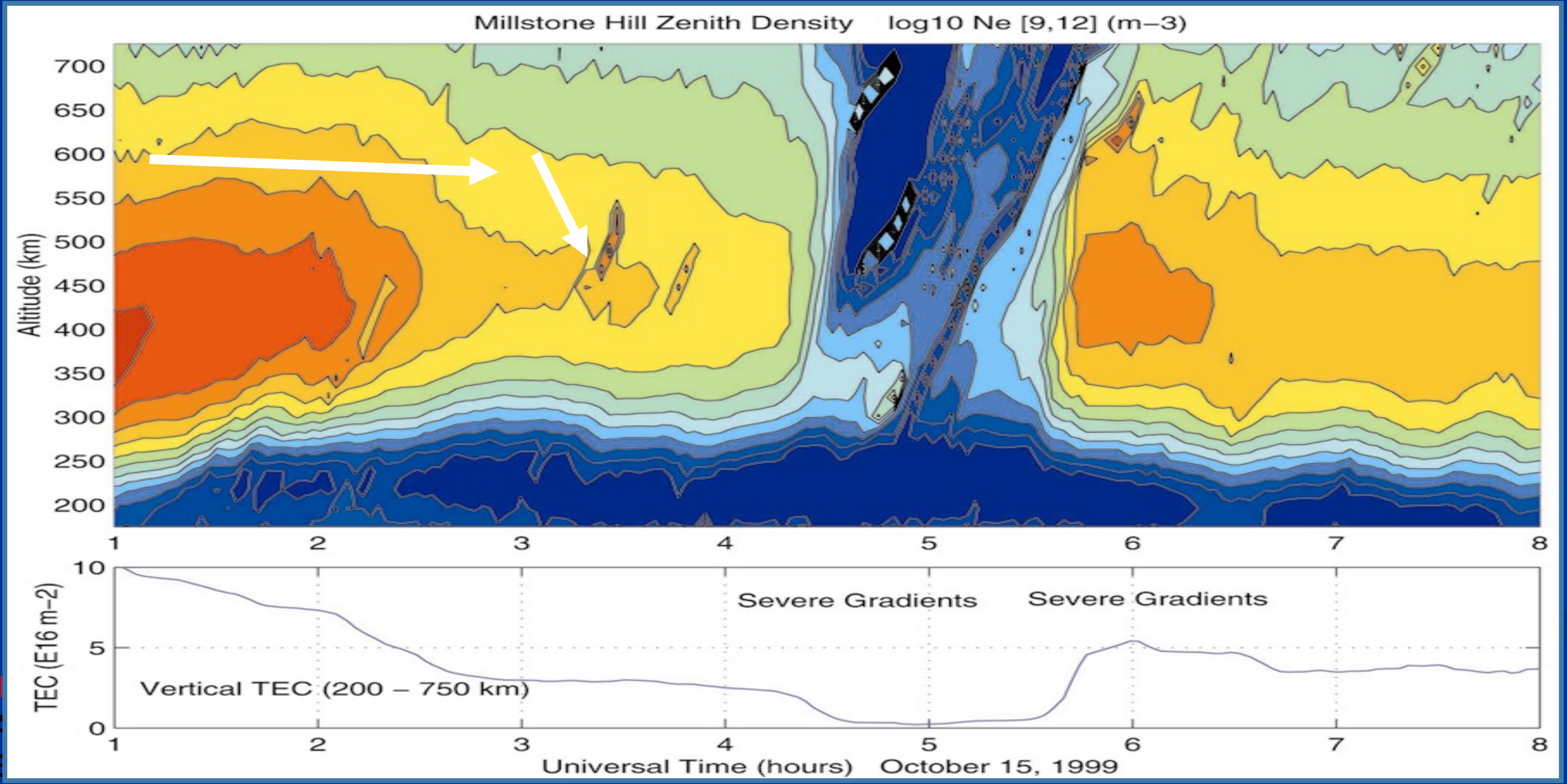
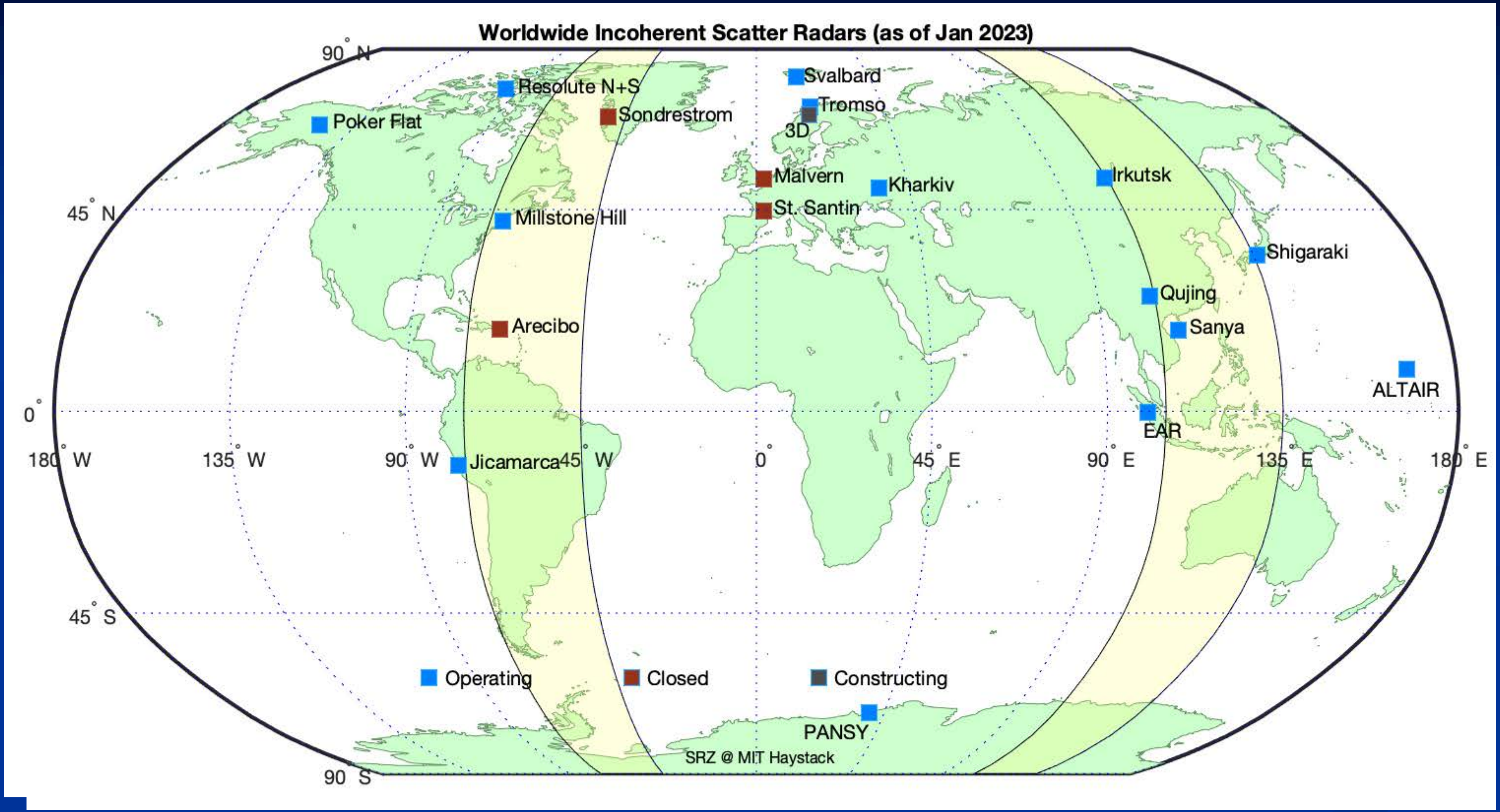
Using ISRs to Measure Space Weather Effects

1. Availability of real-time data
2. Historical data
3. Can we work as a coordinated sensor network?



Global Network of Incoherent Scatter Radars



Can Measure Physical Properties of the Space Environment as a function of altitude:

electron density, electron temperature, ion temperature, plasma velocity

Can Infer:

electric field strength, conductivity, current, neutral air temperature, wind speed

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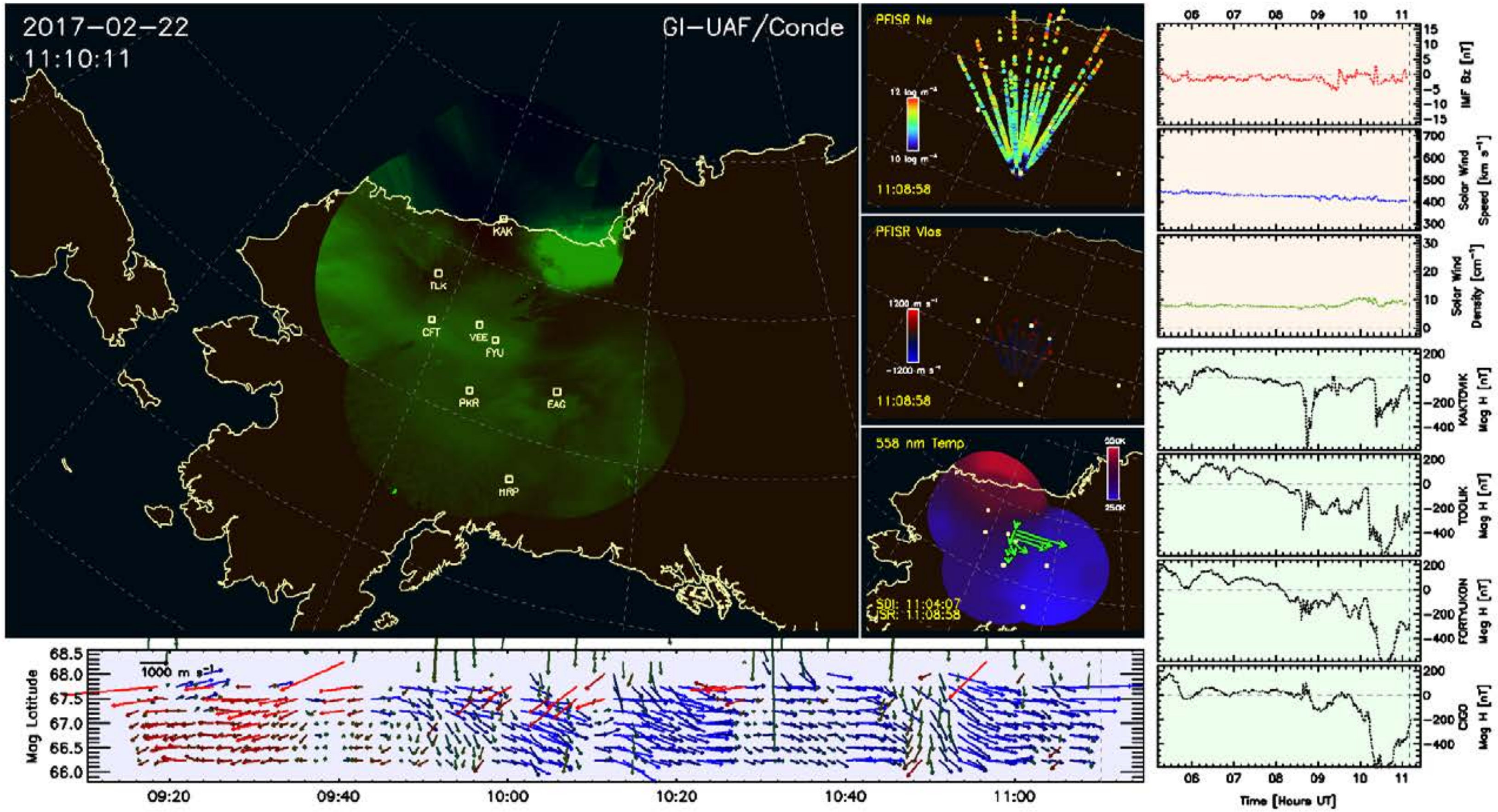
PFISR – High Latitude Radar

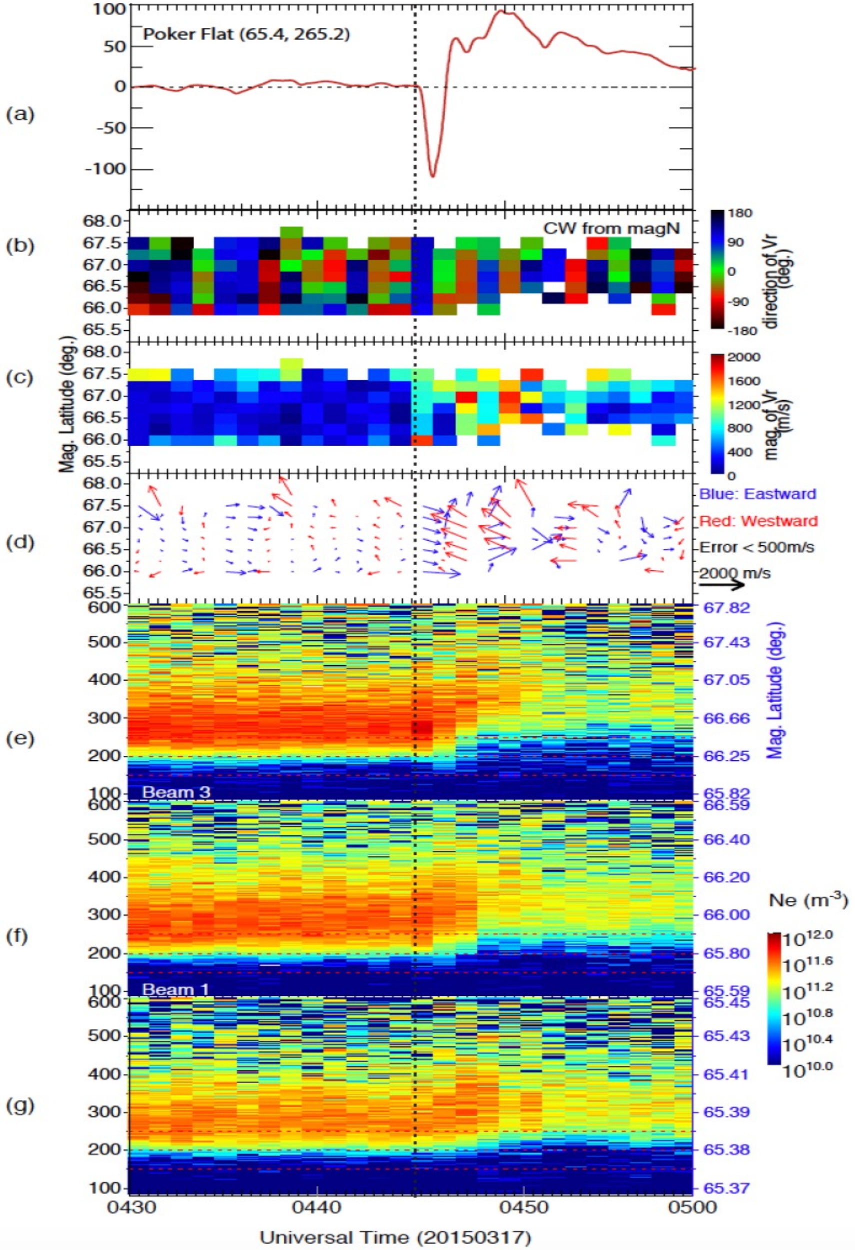
Integrated Real Time Displays at PFRR



- Integrated displays combine PFISR, all-sky cameras, scanning Doppler interferometers, and magnetometers.

PFISR operates continuously

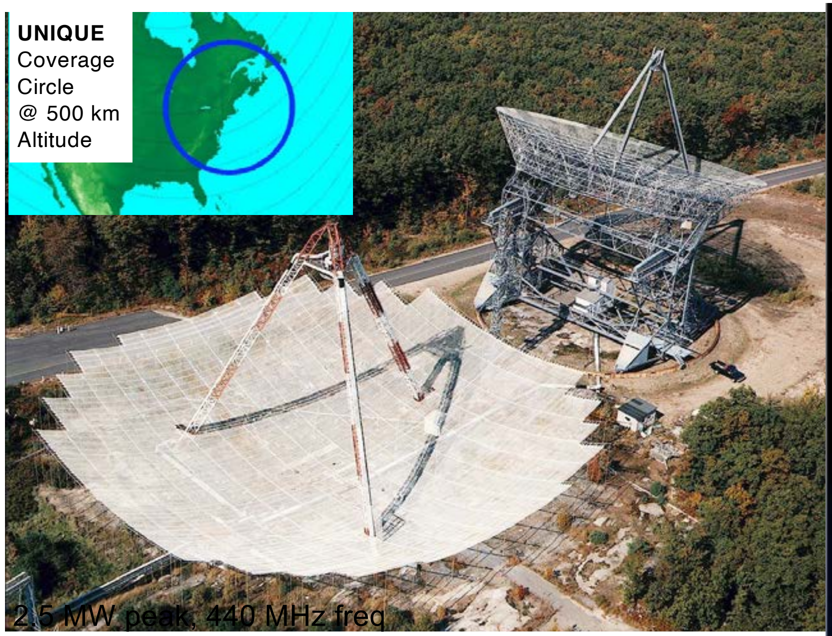
- Continuous operations allow the radar to catch space weather events that are not necessarily well predicted.
- For example, the PFISR IPY mode serendipitously captured to the ionospheric response to the solar wind pressure pulse preceding the 2015-03-17 “St. Patrick’s Day” geomagnetic storm [Zou et al., 2017, GRL].

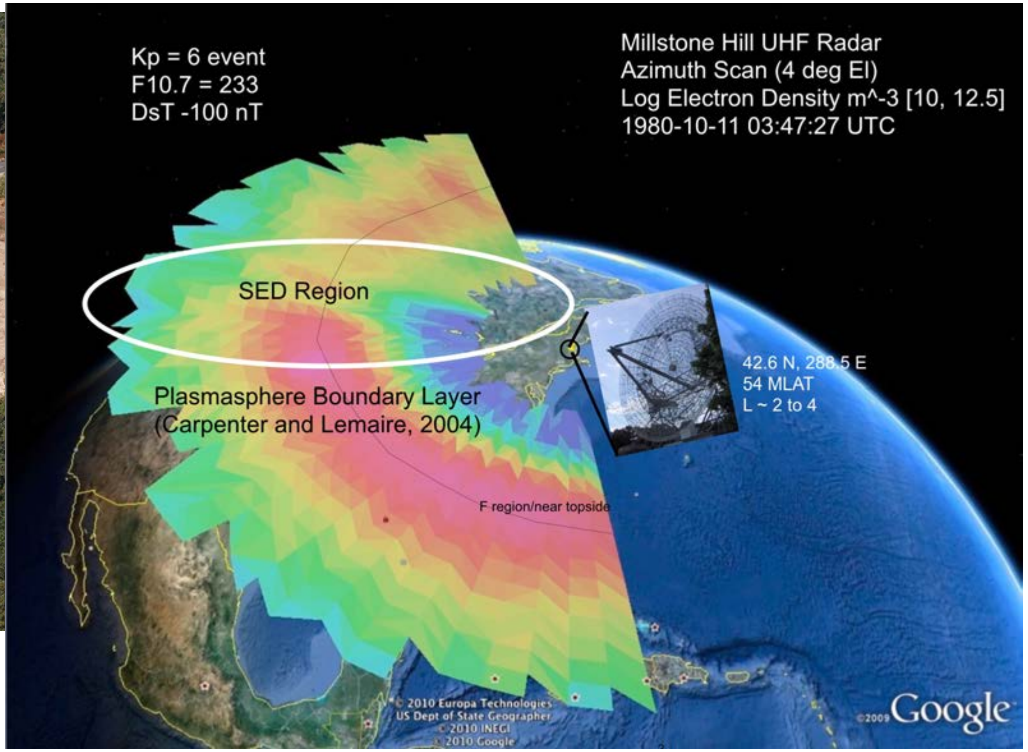


Mid-Latitude Incoherent Scatter Radar – Millstone Hill

Millstone Hill Geospace Facility

Millstone Hill Incoherent Scatter Radar (1960 - present)





- 900-1000 hours/year
- Height-resolved plasma parameters
- Rapid response capability (< 1 hour to activate)
- Very wide field coverage of mid-latitude ionosphere, thermosphere, M-I coupling
- Coupled to frontier programs (e.g. Van Allen Probes, MMS)

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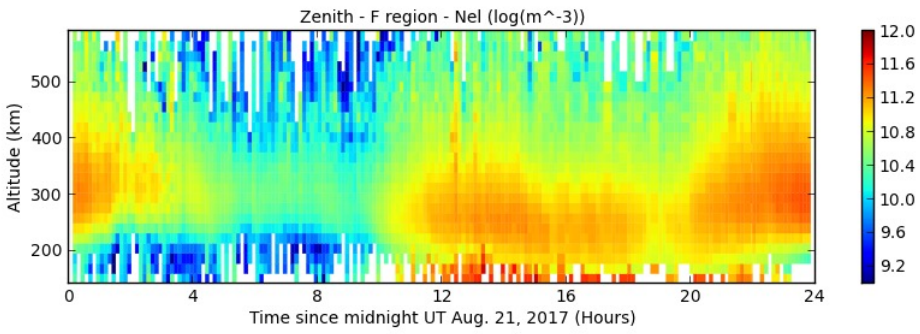
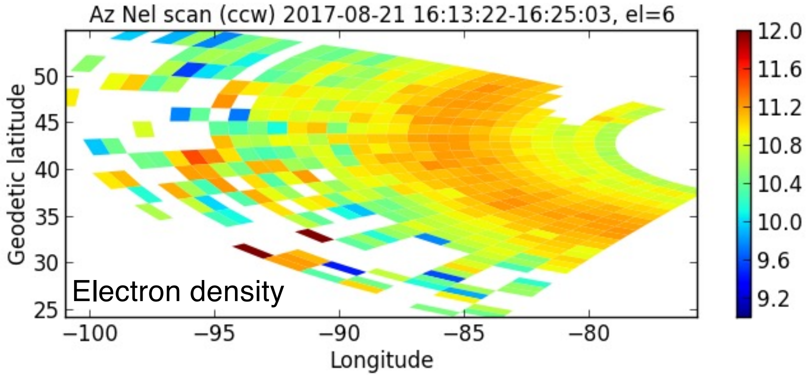
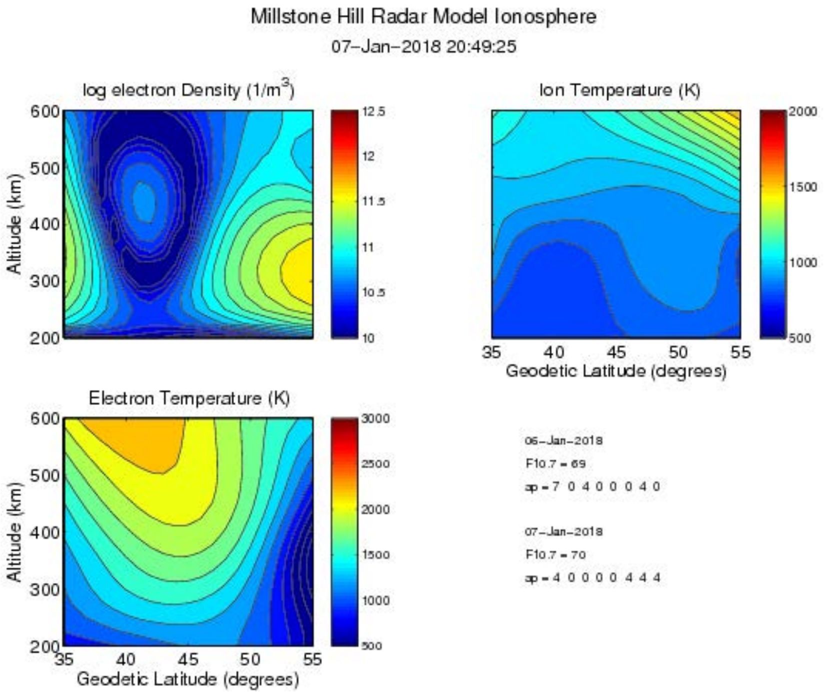
Millstone Hill Geospace Facility
Realtime IS Analysis Capability for Space Weather



Vertical Profiles



Wide field Scan Profiles



ISRIM Empirical ISR Model
Driven by realtime conditions

All radar operations analyzed with ~2-3 minute delay behind real time
Deposited directly in Madrigal system
Observations and empirical model are available right away to users through Madrigal web and software APIs

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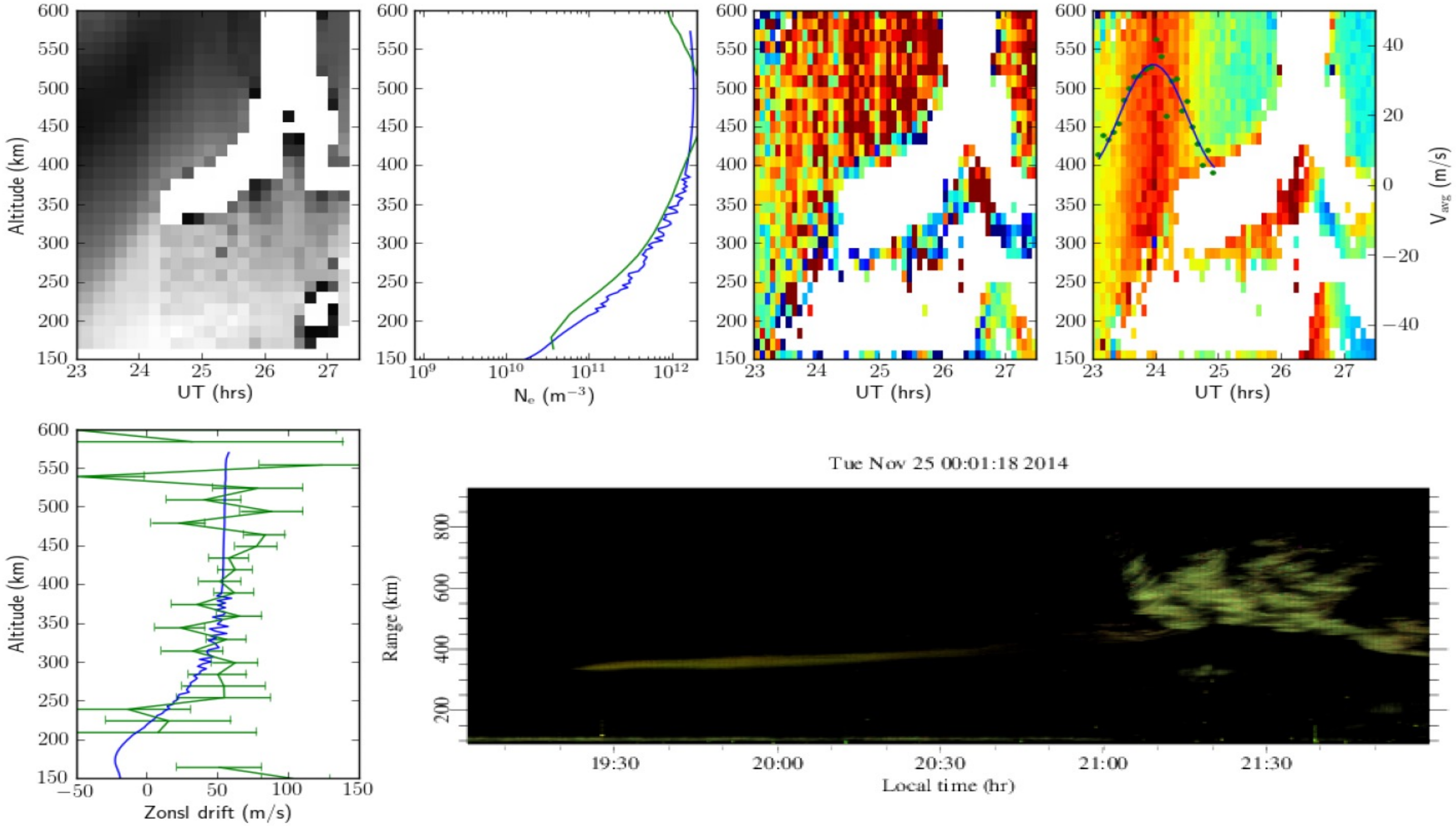
Low Latitude Radar - Jicamarca

Space-weather forecasting at Jicamarca
25 November 2014

postsunset measurements of
plasma density, vertical drift, and zonal drift profiles
with an assessment of ESF activity



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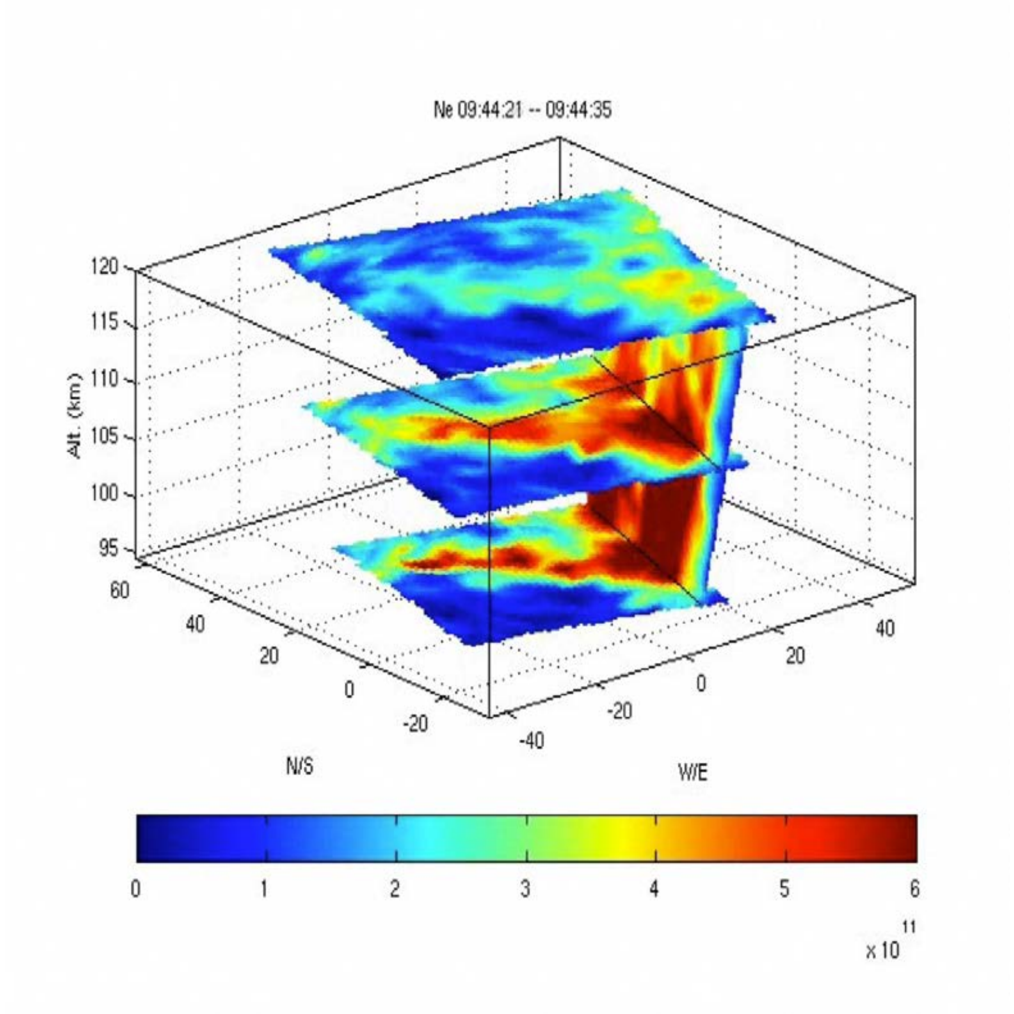
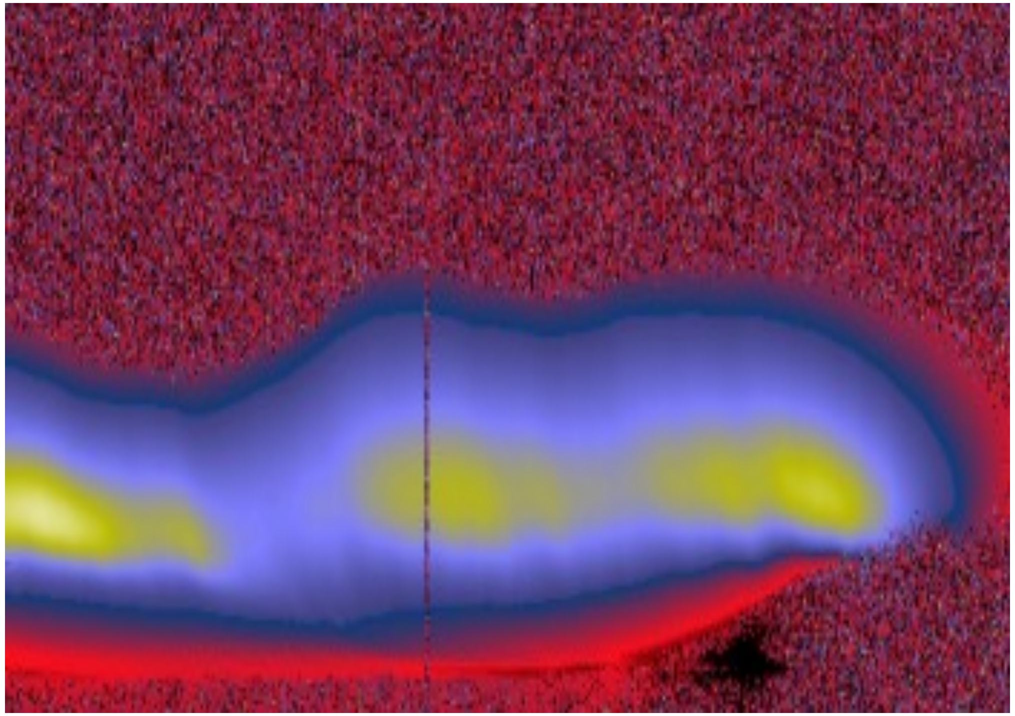
In Summary …..



Incoherent Scatter Radars provide detailed looks into ionospheric properties and dynamics



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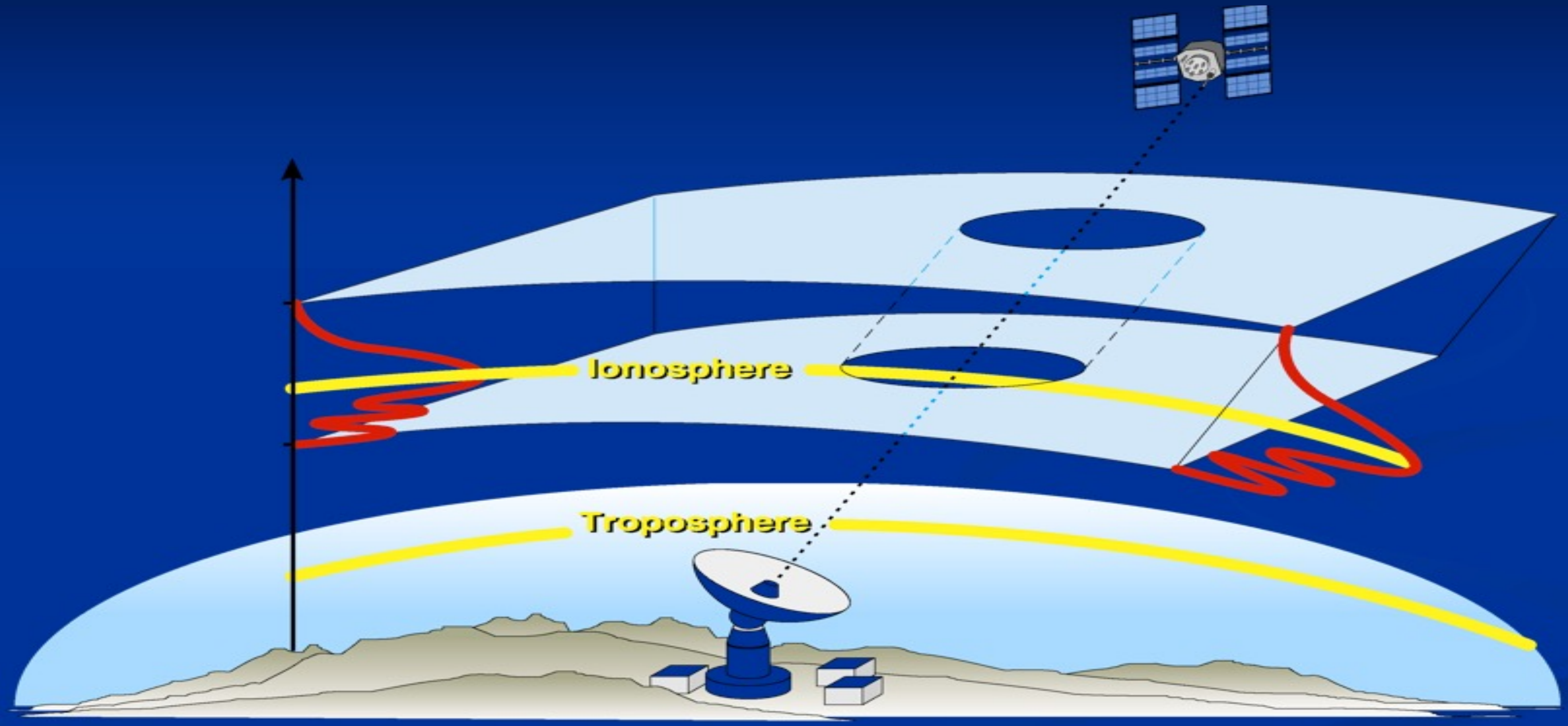
Definition:

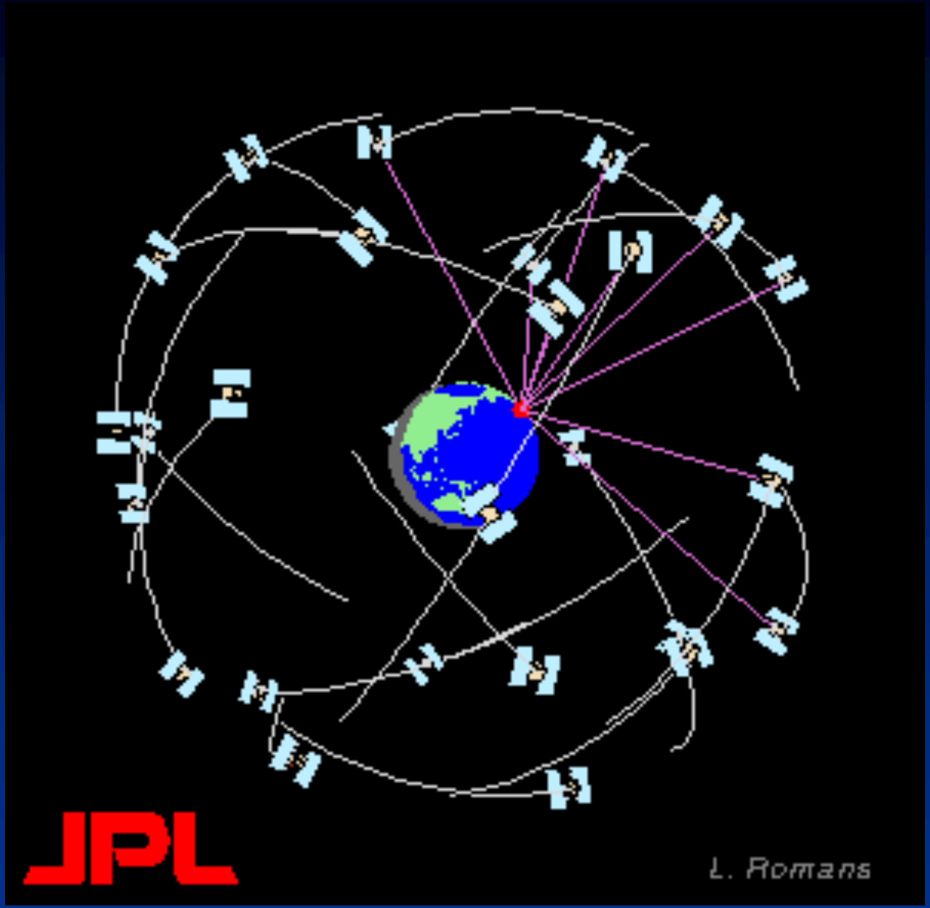
TEC = Total Electron Content (10^{16} x el/m^2)

$$\Delta R_{ion}(meters) = \frac{40.3}{f^2}\,TEC$$

Satellites transmit/receive radio wave signals that propagate through the atmosphere

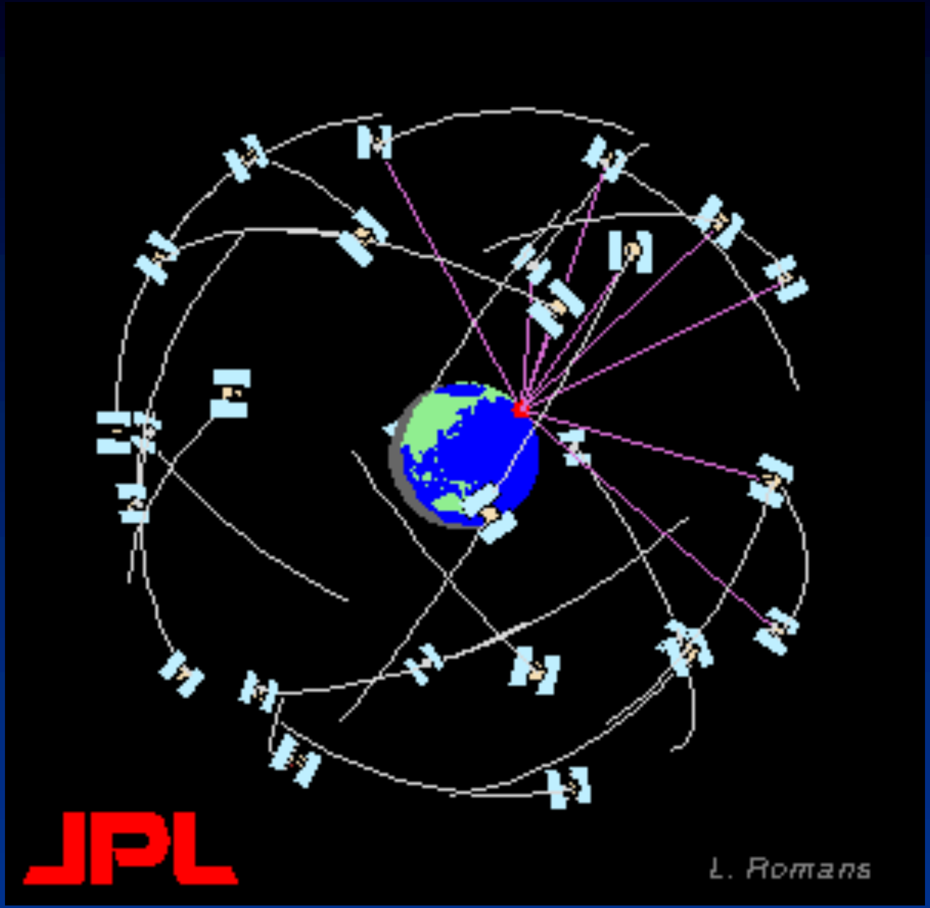


From Attila Komjathy, JPL



GPS Background

- At most 32 satellites
- 6 orbital planes
- 4~6 satellites per plane
- 55^{o} inclination angle
- near circular orbit
- ~ 20000 km altitude
- ~12 hours round trip
  (11 hour 58 min 2.05 sec)

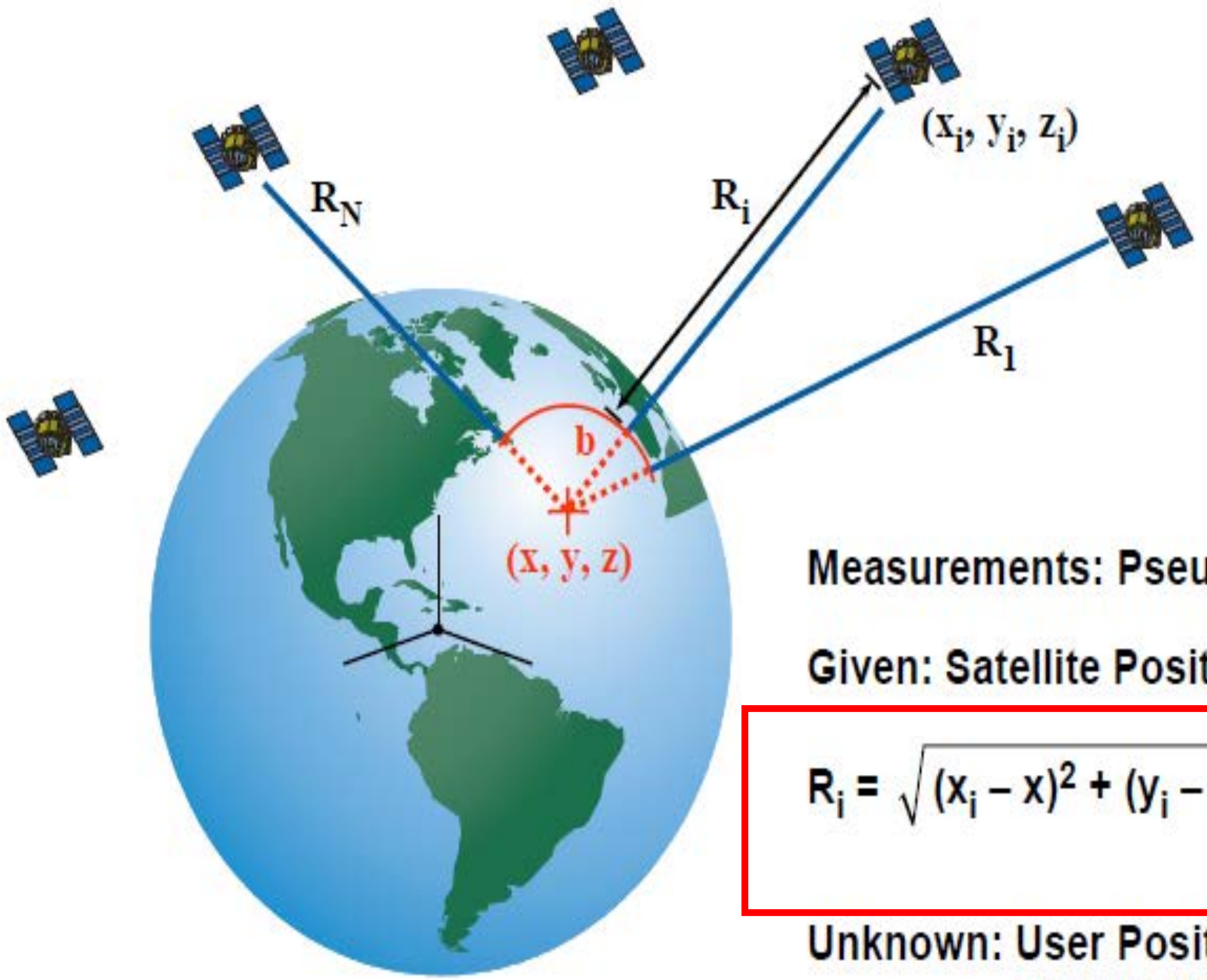


GPS Background

Each GPS spacecraft:

- Carries highly accurate clock
- Transmits its clock and position
- Signals are transmitted on 2 (or 3) frequencies
- First satellites launched in 1978
- Fully operational in 1995 (19 in 1991)

GNSS Positioning



Error Sources:
- Ephemeris Error
- GPS Clock Error
- Receiver Noise
- Multipath
- Atmosphere:
  - Troposphere
  - Ionosphere

Measurements: Pseudoranges $\{R_i\}$

Given: Satellite Positions $\{(x_i, y_i, z_i)\}$

$$R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - b, \quad i = 1, 2, \ldots, N$$

Unknown: User Position (x, y, z)
Receiver Clock Bias b

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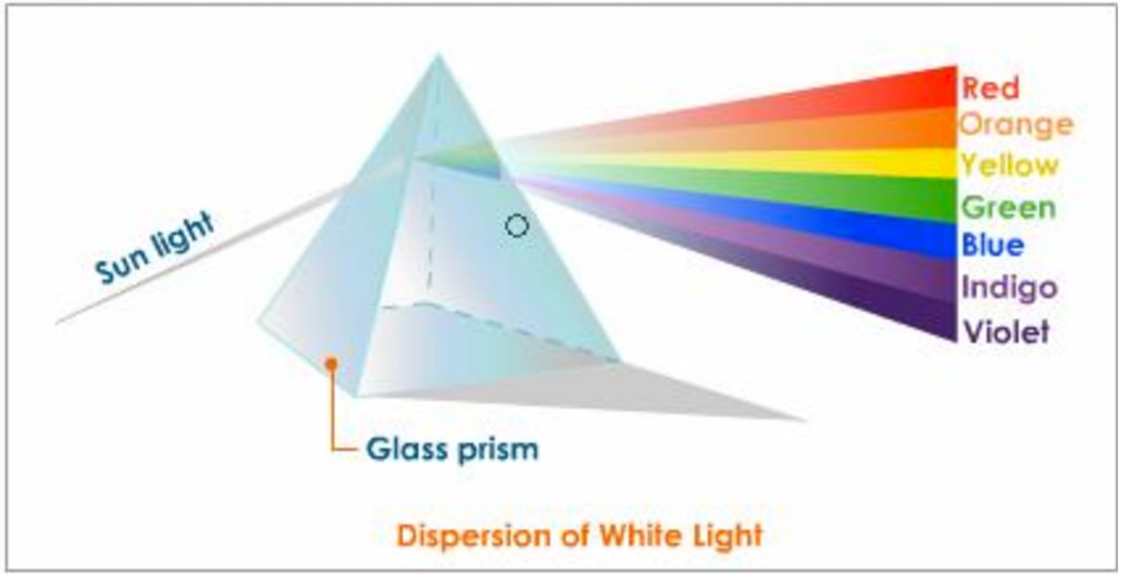
Refraction and Dispersion

$$n = \frac{c}{v_{\mathrm{p}}}.$$



Index of Refraction $n = \frac{c}{v_p}$. in the Ionosphere

$$n^2 = 1 - \frac{X(1-X)}{(1-X) - \frac{1}{2}Y_T^2 \pm \left(\frac{1}{4}Y_T^4 + (1-X)^2 Y_L^2\right)^{1/2}}$$

where

n is the index of refraction

$$X = \frac{\omega_N^2}{\omega^2} \qquad Y = \frac{\omega_H}{\omega} \qquad \omega_N = \left(\frac{Ne^2}{\varepsilon_0 m_e}\right)^{1/2} \qquad \omega_H = \frac{e|B|}{m_e}$$

ω = the angular frequency of the radar wave,

$Y_L = Y\cos\theta$, $Y_T = Y\sin\theta$,

θ = angle between the wave vector $\bar{k}$ and $\bar{B}$,

$\bar{k}$ = wave vector of propagating radiation,

$\bar{B}$ = geomagnetic field, N = electron density

e = electronic charge, m_e = electron mass,

and ε_0 = permittivity constant.

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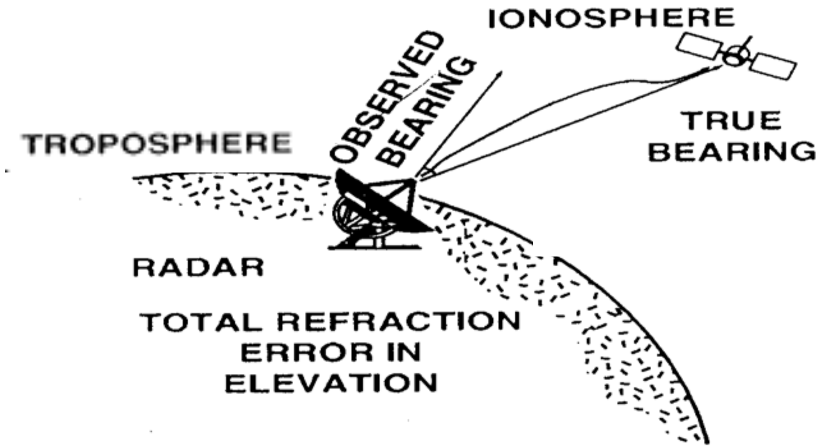
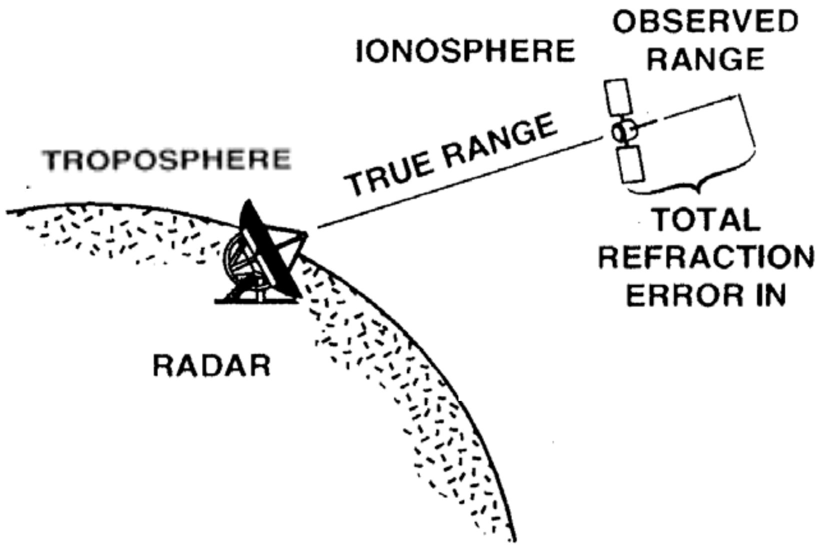
Illustration of Atmospheric Effects

Elevation Refraction



Range Delay



Ionospheric Range Correction

$$n \approx \left(1 - \frac{\omega_N^2}{\omega^2}\right)^{\frac{1}{2}} \approx 1 - \frac{\omega_N^2}{2\omega^2} \approx 1 - \frac{AN_e}{f^2}$$

$$\Delta R_{ion}(meters) = \frac{40.3}{f^2} \int_0^R N_e \, dr$$

Range Delay

TEC	S-Band	L-Band	UHF	VHF	Elev	Mapping Function
50	2.4 m	12 m	104 m	787 m	90 °	x 1
110	5.1 m	26 m	223 m	1.7 km	20 °	x 2.12

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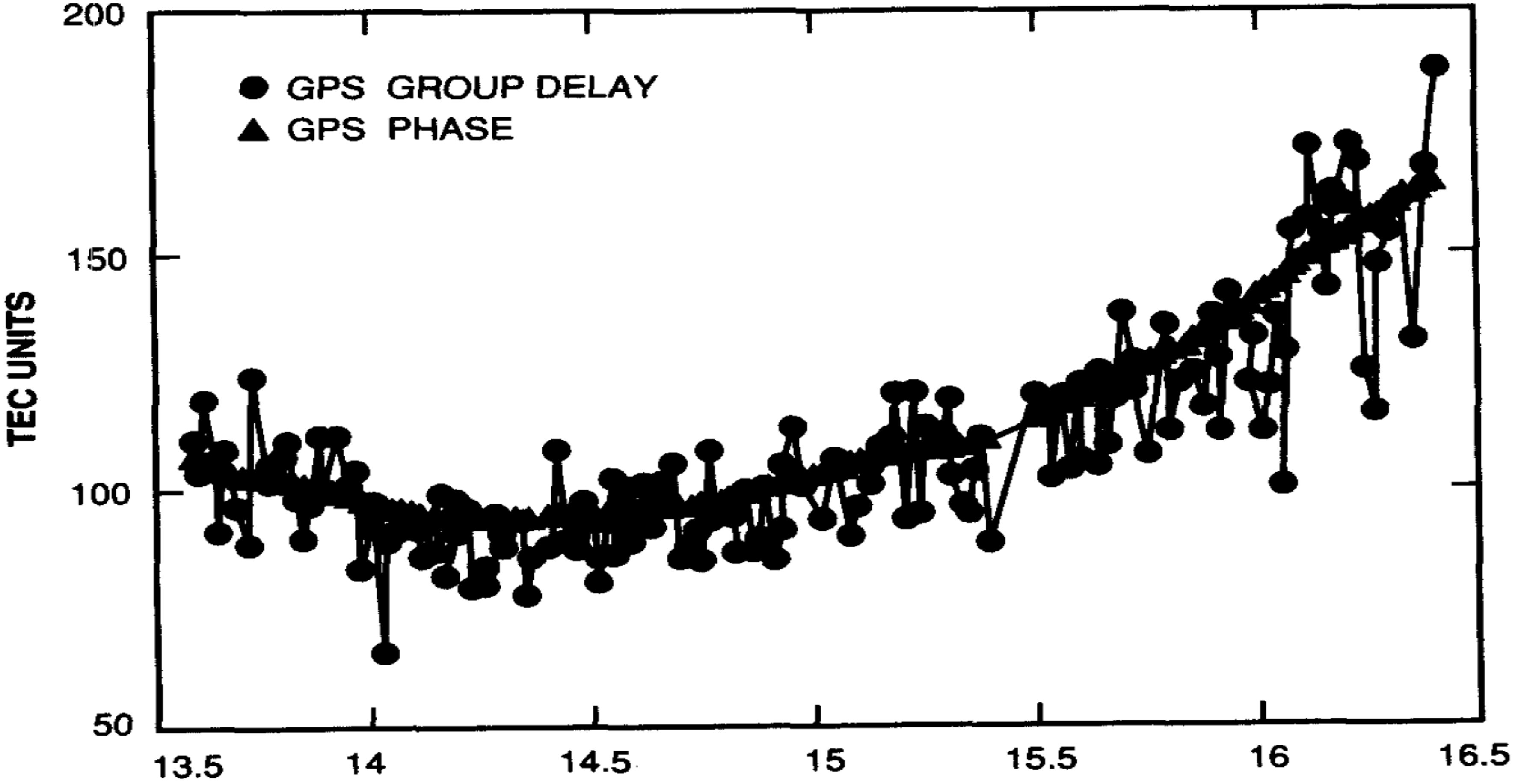
TEC from GPS is measured from the difference of the GPS pseudo-range measurement at two frequencies

$$P_1 - P_2 = 40.3TEC\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right)$$

$$TEC = \frac{1}{40.3}\left(\frac{f_1 f_2}{f_1 - f2}\right)(P_2 - P_1)$$

Where P1 and P2 are the pseudo-ranges measured by GPS at the two different frequencies, f1 and f2.

Illustration of GPS Phase and Group Delay TEC data. GPS Sv 6. 1 March 1989



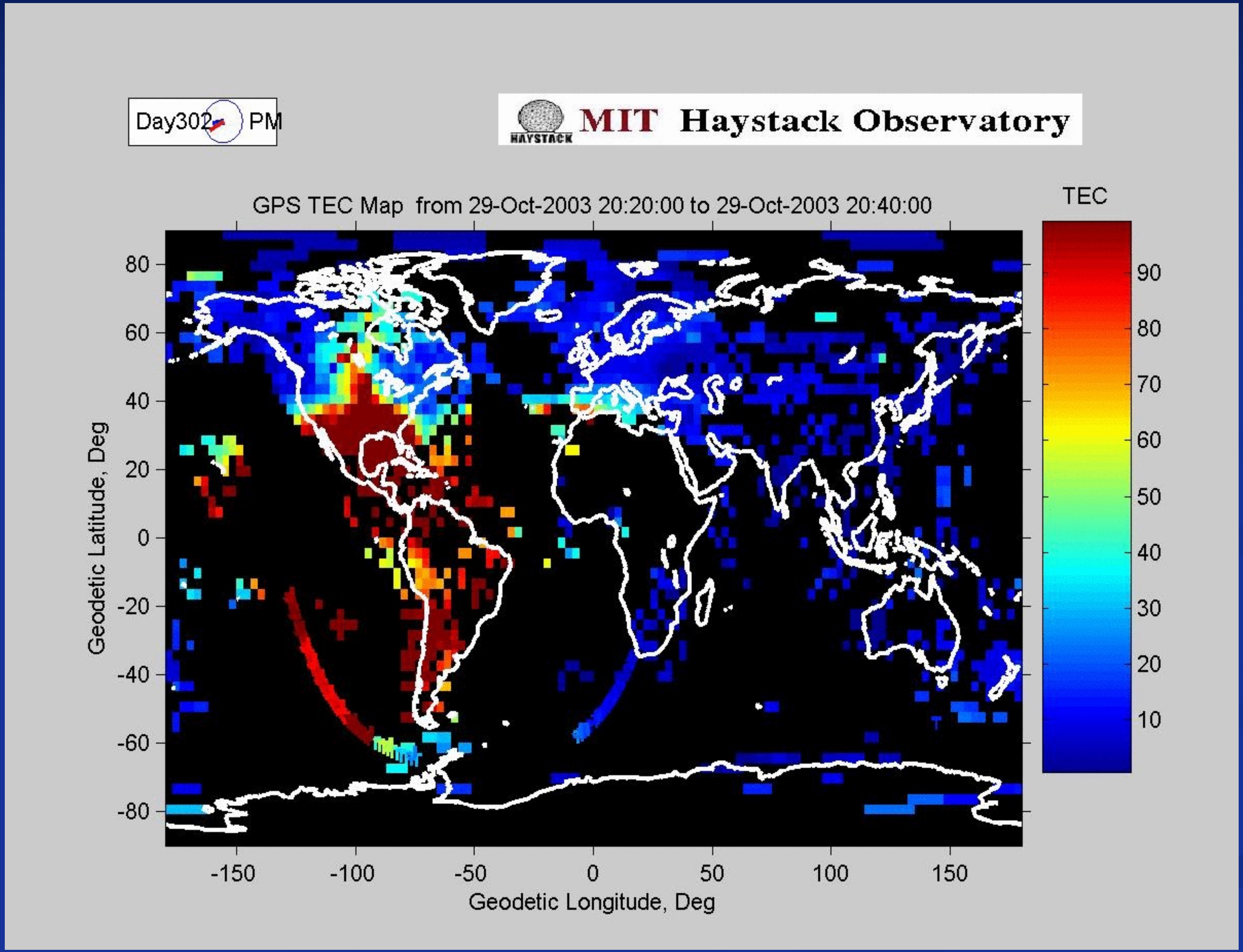
Coster, A. J., E. M. Gaposchkin, and L. E. Thornton, (1992). Real-Time Ionospheric Monitoring System Using GPS, Navigation, Vol. 39, No.2, Summer 1992.

Wide Area Distribution of 'Raw' Information

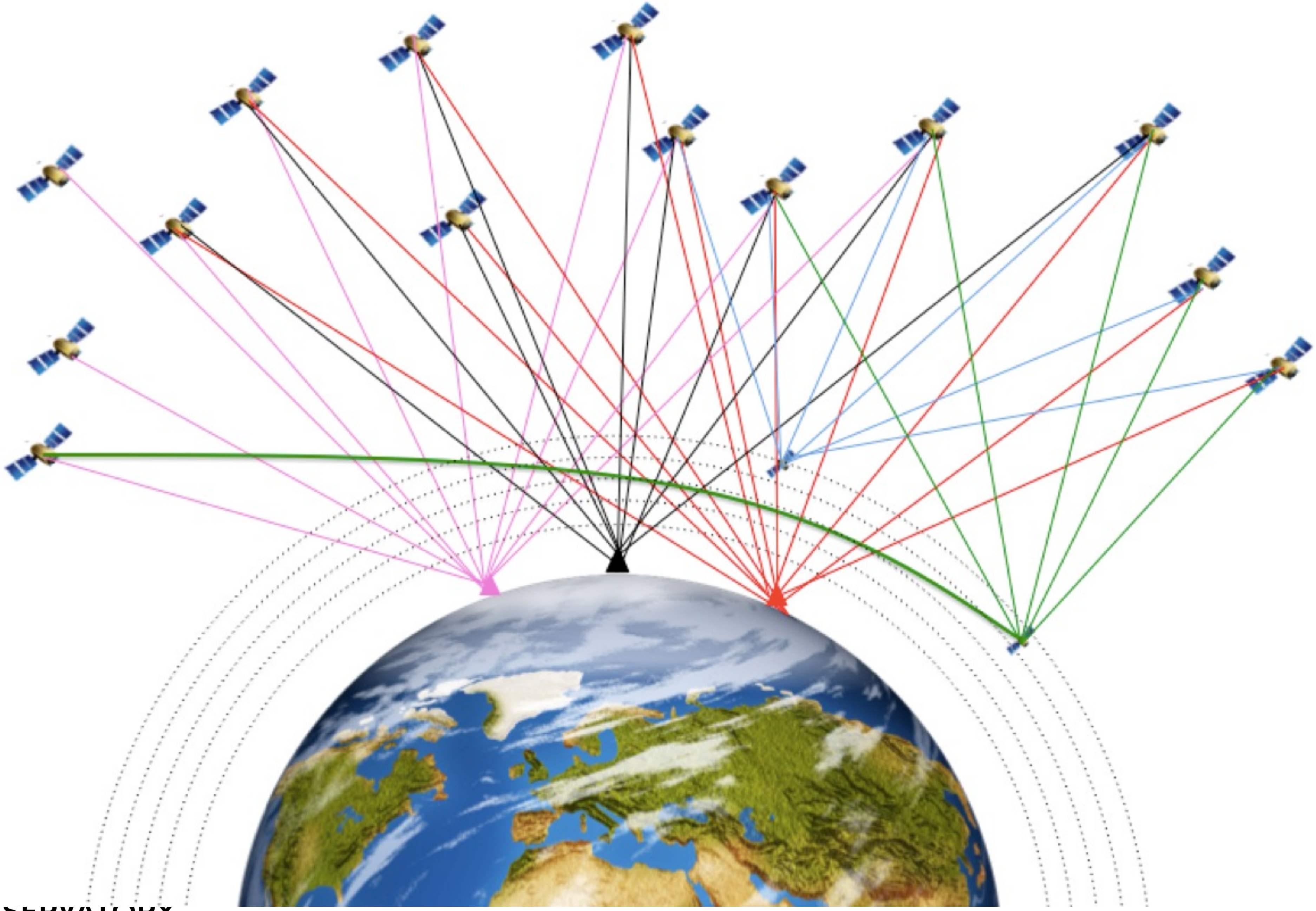
Distributed networks of sensors yield global physics unattainable with single-point measurements

Example :

Global GPS-derived ionospheric mapping durig geomagnetic disturbances



[Coster et al, 2003]



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Quiz:

How many GPS satellites are needed for a fully operational system? How many are in operation now. (in chat)

Name some of the different PNT constellations. (in chat)

Approximately how many pairs of signals are available among the different constellations?

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Ionospheric Parameters GNSS can be used to measure

Ground-Based Receivers

- Total Electron Content (TEC)
- Scintillation Parameters: S_4 and σ_Φ

Space-Based Receivers

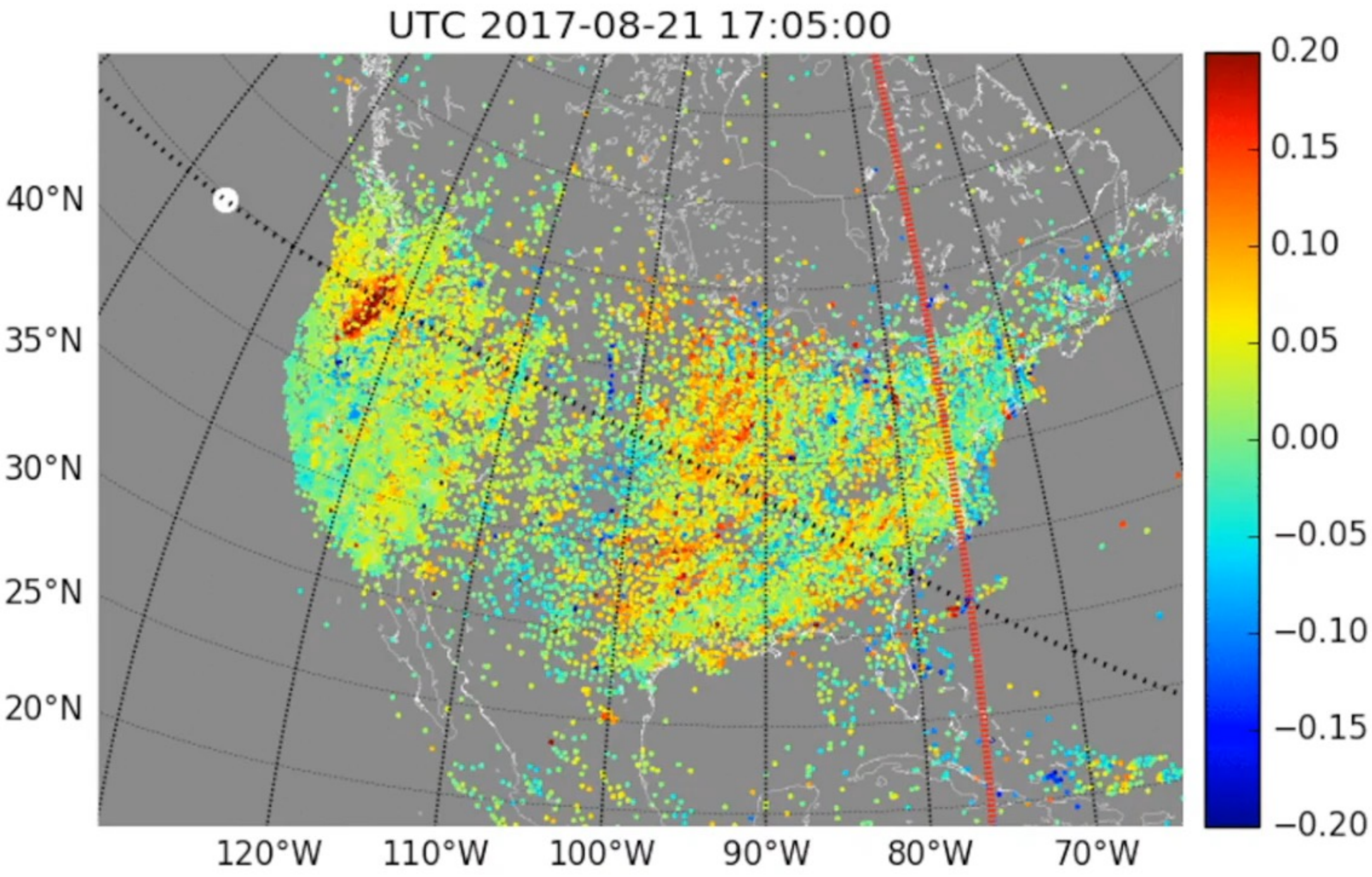
- Electron Density Profiles (EDP)
- Scintillation Parameters: S_4 and σ_Φ

$S4 = \mathrm{sqrt}\,((<I^2> - <I>^2)/<I>^2)$, where

I is the intensity of the signal and <> is the ensemble mean.

$\sigma_\Phi = \mathrm{sqrt}((<\Phi^2> - <\Phi>^2)$, where Φ is the phase of the signal.

2017 eclipse created ionospheric "bow waves"



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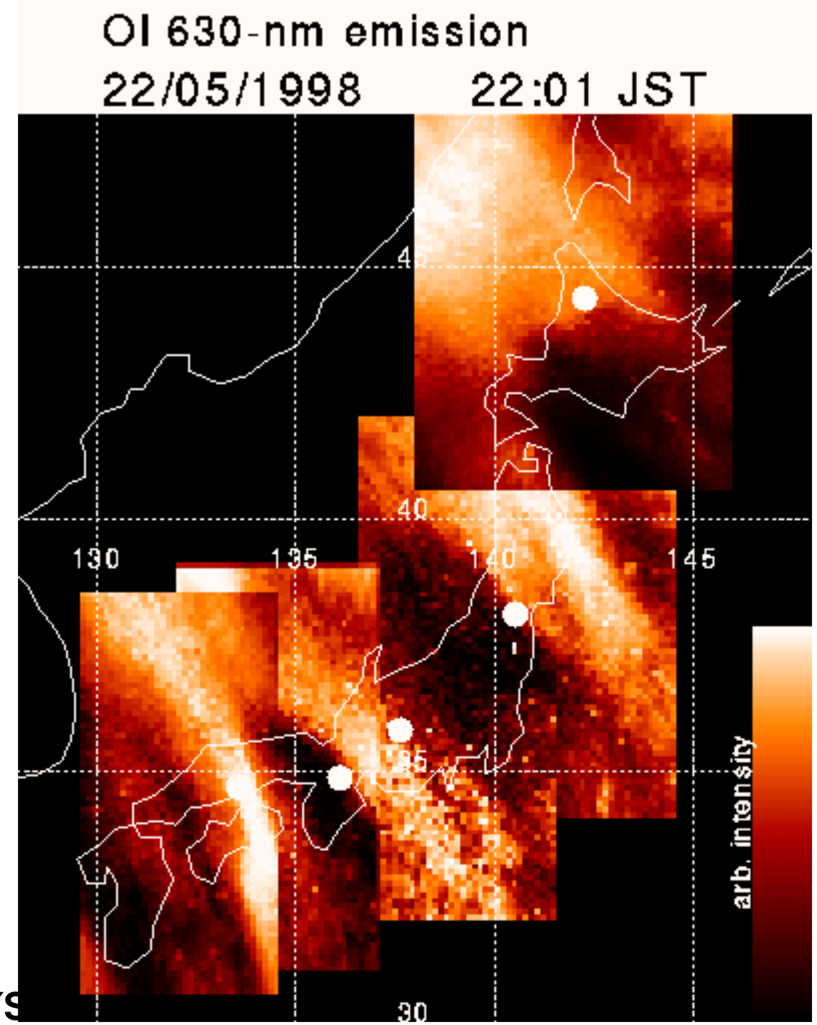
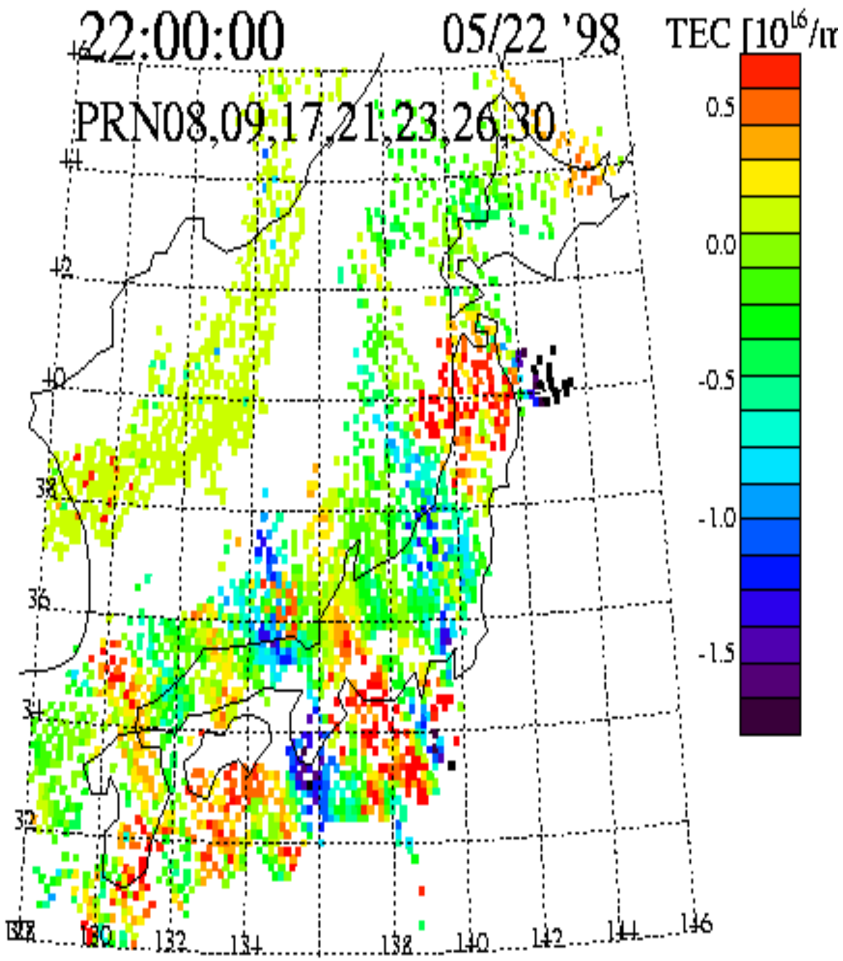
Nighttime MSTID Observations (TEC, Airglow) [*Saito et al.*, 2001]





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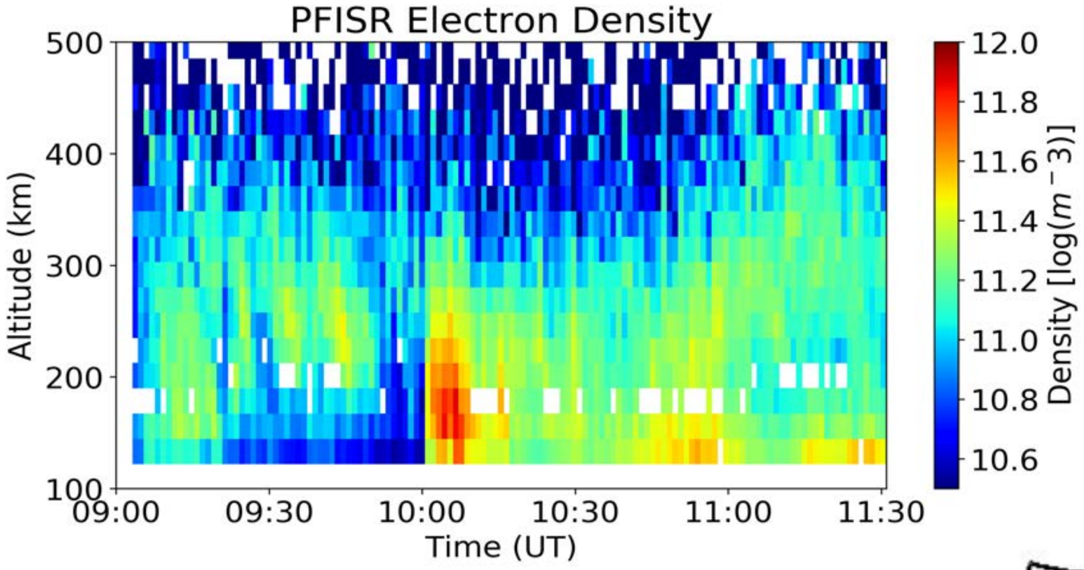
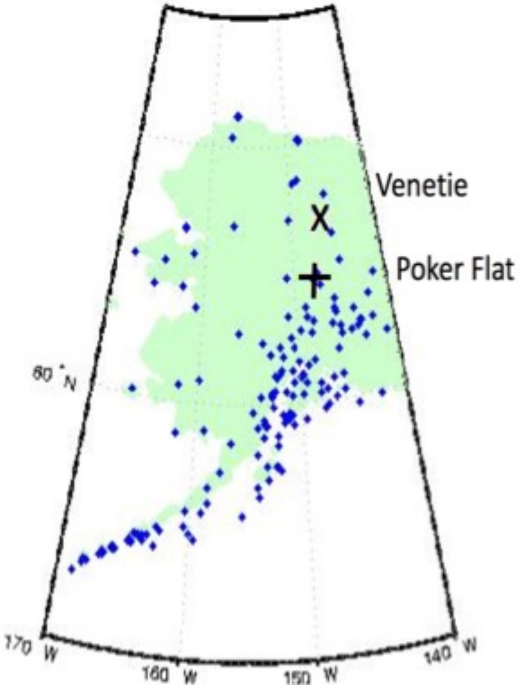
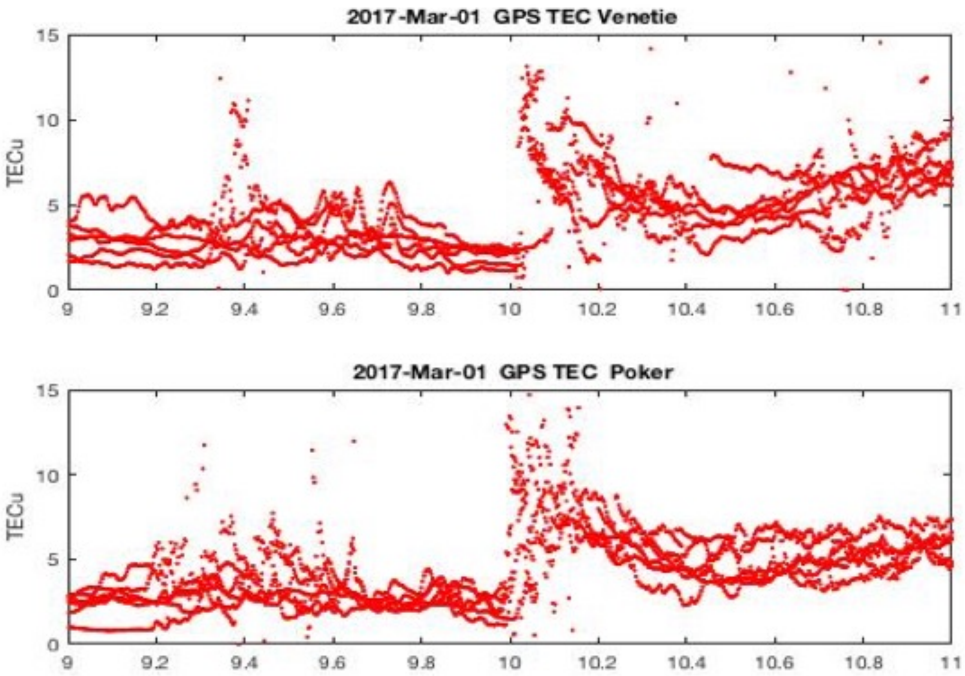
Advantages of combining data sets







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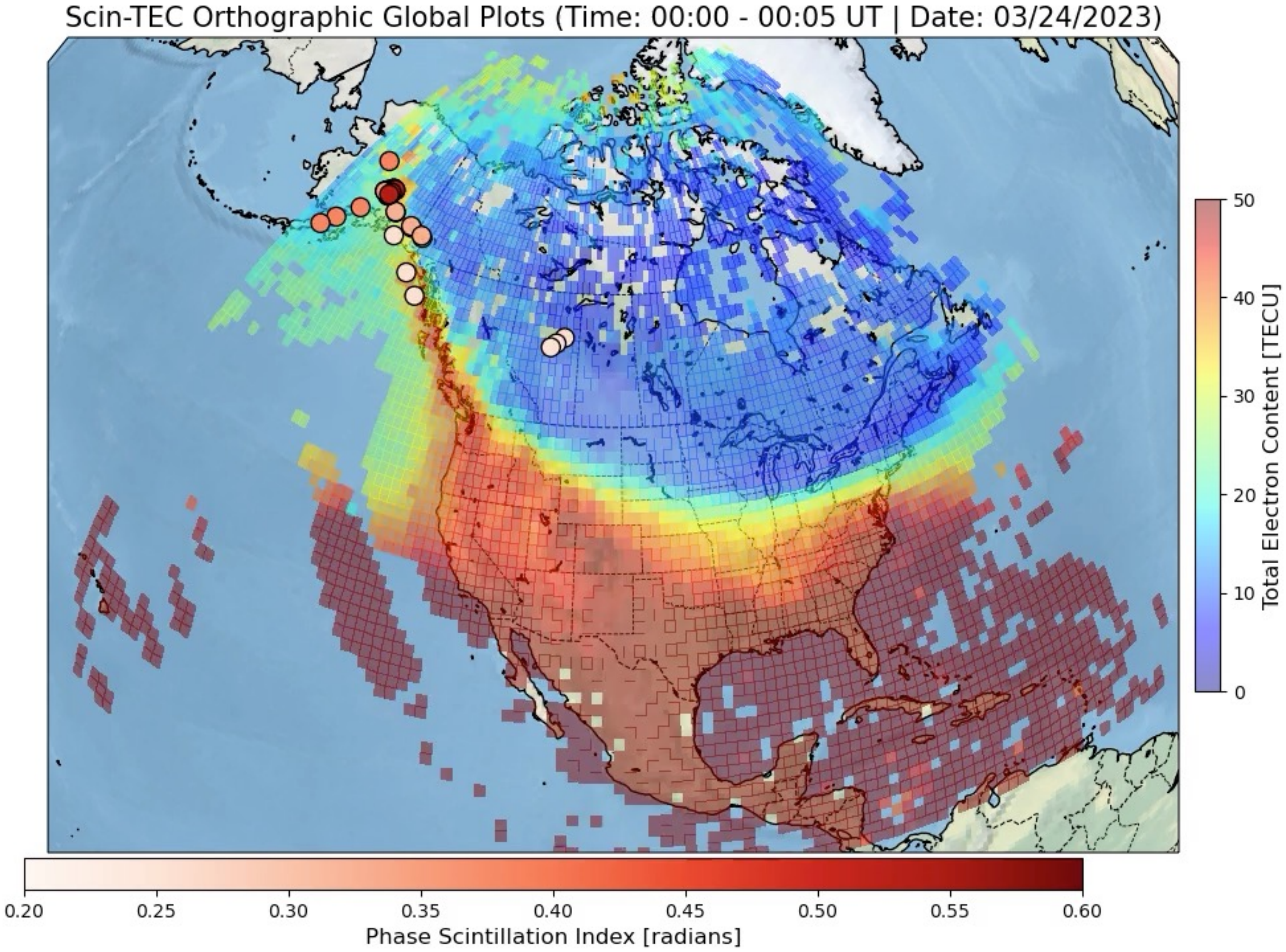
March 23, 2023



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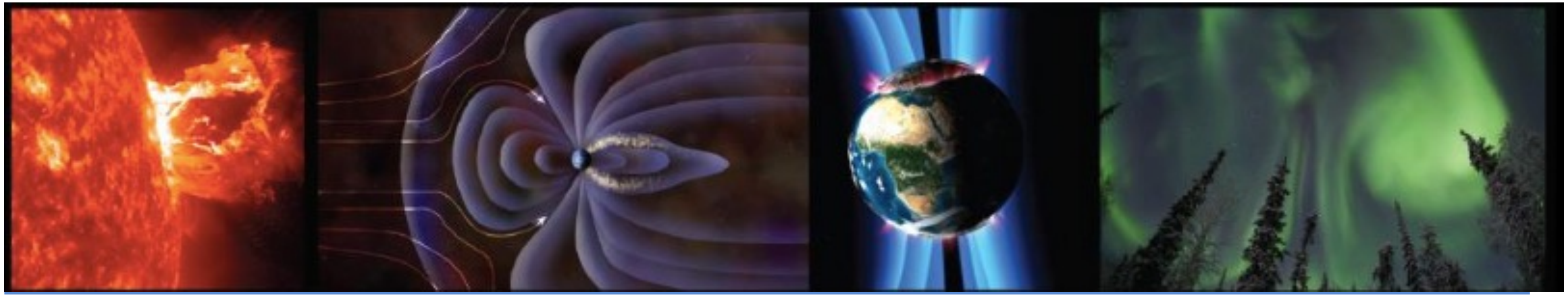
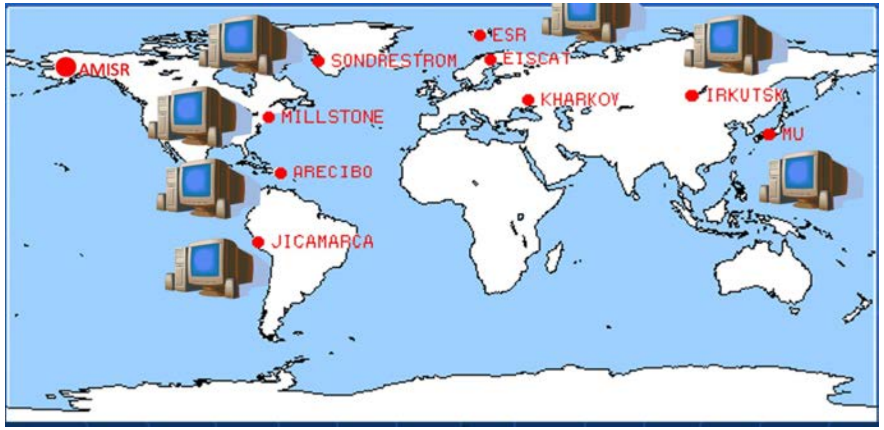


The MADRIGAL Database

http://cedar.openmadrigal.org/index.html/

Madrigal is an upper atmospheric science database used by groups around the world. The US National Science Foundation supports it.



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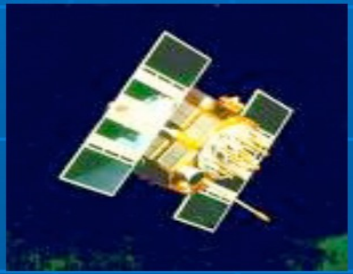
The Madrigal database stores data from a wide variety of upper atmosphere research instruments

Incoherent Scatter Radar

TEC via GPS

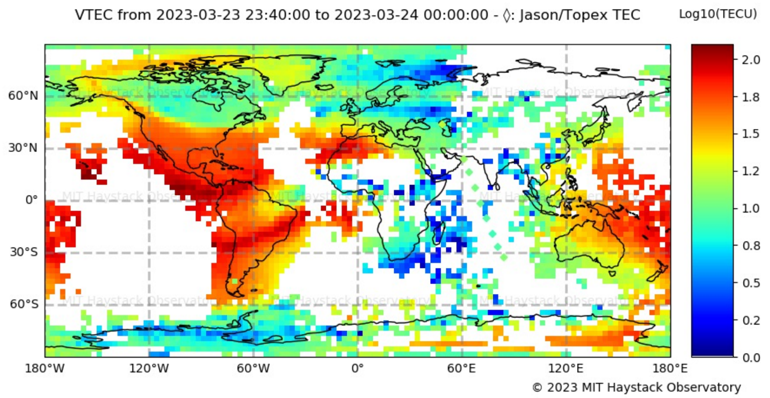


MF Radar

Number of instruments in Madrigal:

- Incoherent scatter radars: 22
- MST radars: 3
- MF radars: 16
- Meteor radars: 7
- FPI: 23
- Michelson Interferometers: 6
- Lidars: 4
- Photometers: 4

Standard TEC Data in Madrigal available since 2000



1. Provided in 1 degree by 1 degree bins
2. Provided every 5 minutes
3. Provides Vertical TEC data estimates and Errors
4. Geographic Lat and Long
5. Only provides data where observations are available. ***Does not attempt to model TEC where data is not available. Uses all GNSS data available.***
6. GLONASS observations and in some cases BEIDOU TEC observations have been included

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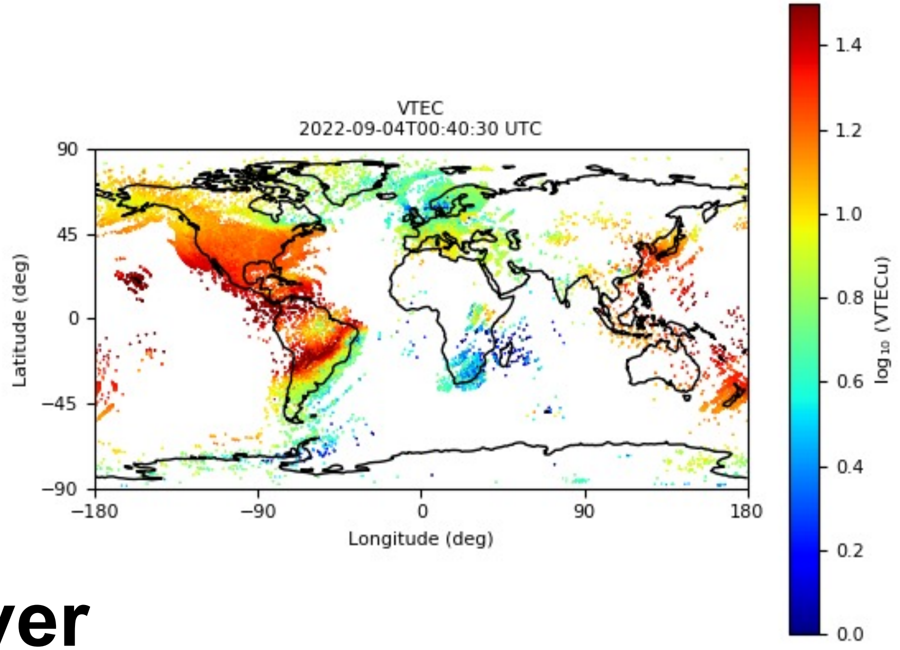
http://cedar.openmadrigal.org/

Line of Site TEC Data in Madrigal available now for ~ 8 years

1. Provided for every receiver
2. Provided every 20 second
3. Satellite and Receiver ID
4. Geographic Lat and Long of Receiver
5. Pierce Point: Altitude, Lat and Long
6. Azimuth and Elevation to Satellite
7. Files are LARGE
8. HDF5 format



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http://cedar.openmadrigal.org/

Summary:

- *Find easier ways to integrate different data types*
- *Utilize all signals*
- *Improve visualization data sets*
- *Standardize data formats*
- *Make everything easily accessible*
- *Modelers, data scientists, experimentalists: COLLABORATE*

Figure courtesy Shun-Rong Zhan