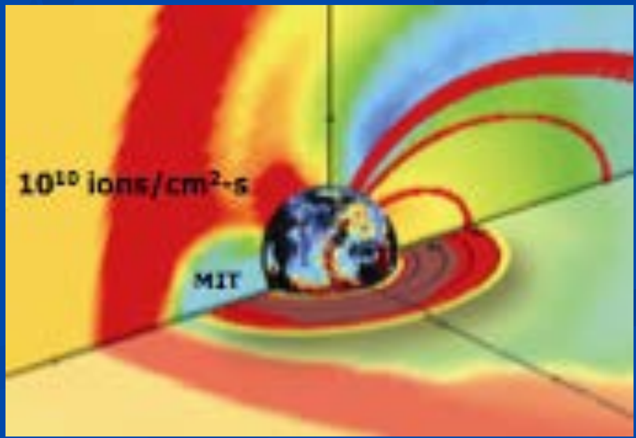
A Student Tutorial : Using GPS to Study Magnetospheric-Ionospheric Coupling

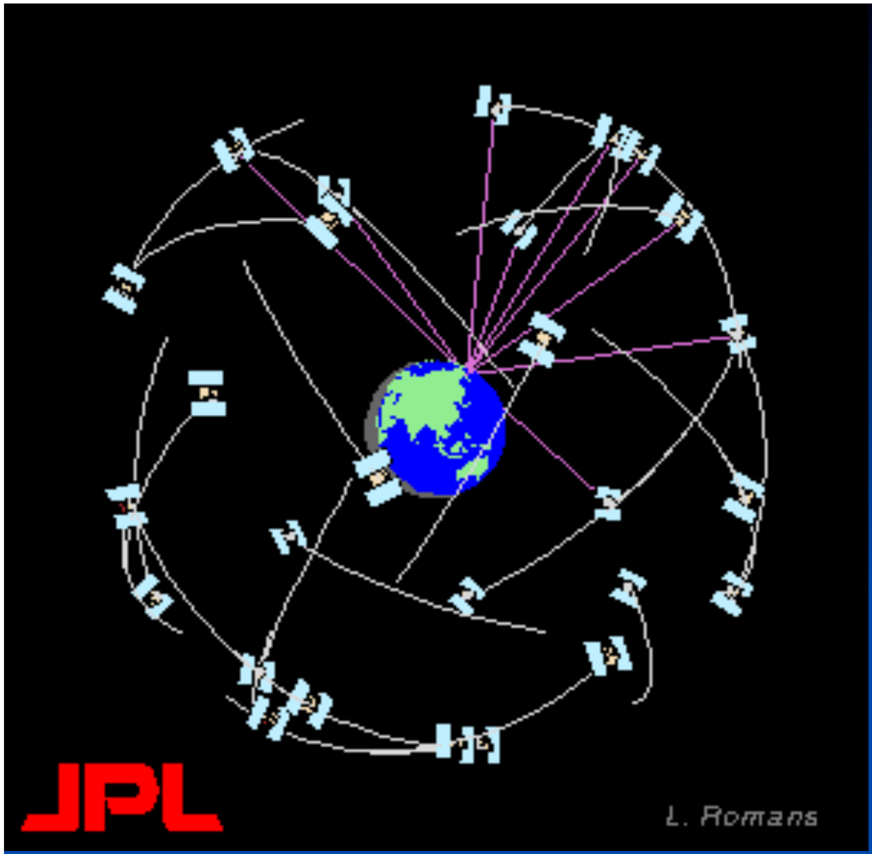
Anthea Coster

MIT Haystack Observatory



Outline

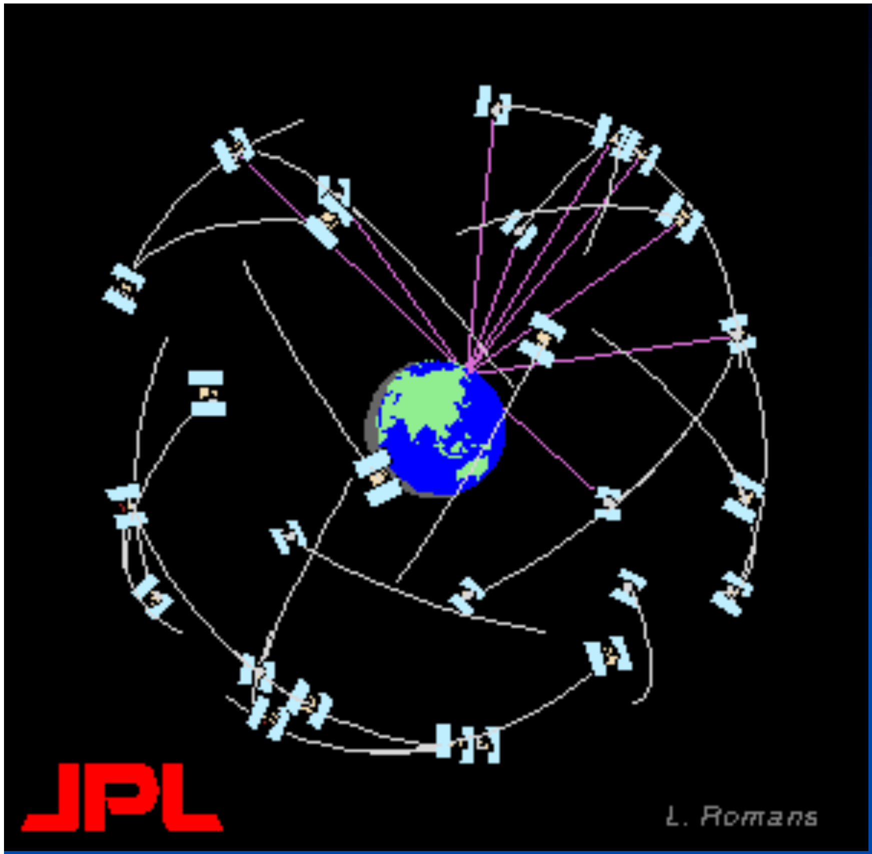
- ABC's of GPS
- History (some) of measuring the ionosphere with GPS
- IT Coupling – GPS
- MI Coupling – GPS
- What's on the horizon



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

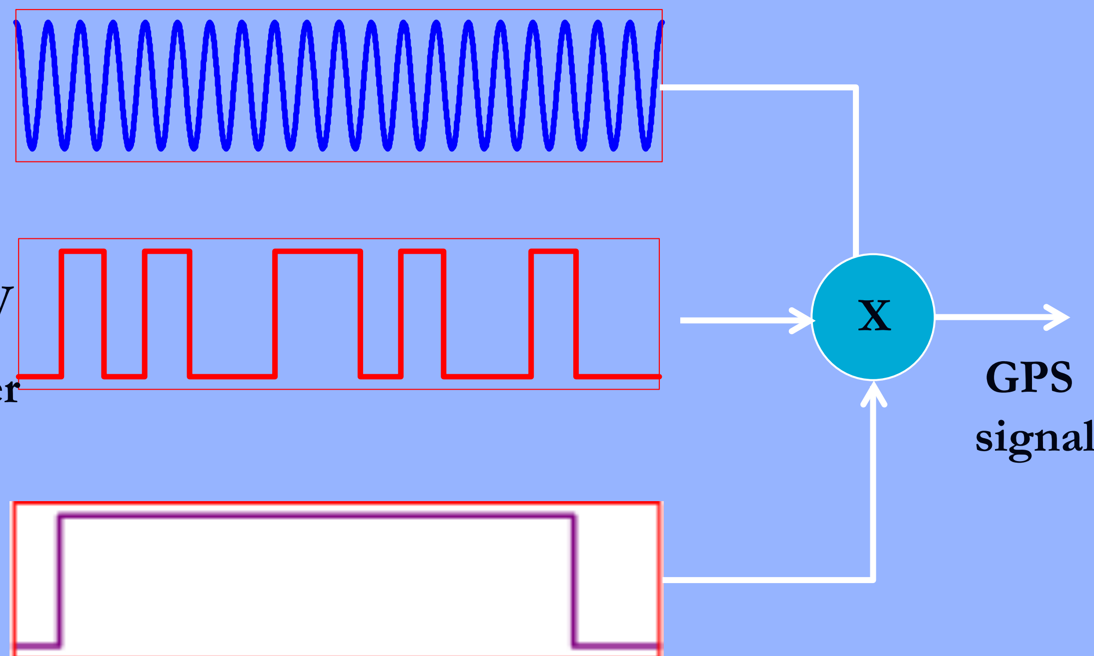
•Signals are transmitted on 2 (or 3) frequencies

GPS Satellite Signal Structure

- Carrier
  - Doppler
  - Range

Code modulation:
  - Identifies SV
  - Spread power
  - Range

Navigation data
  - SV orbit
  - Error correction
  - SV health



Range Measurements

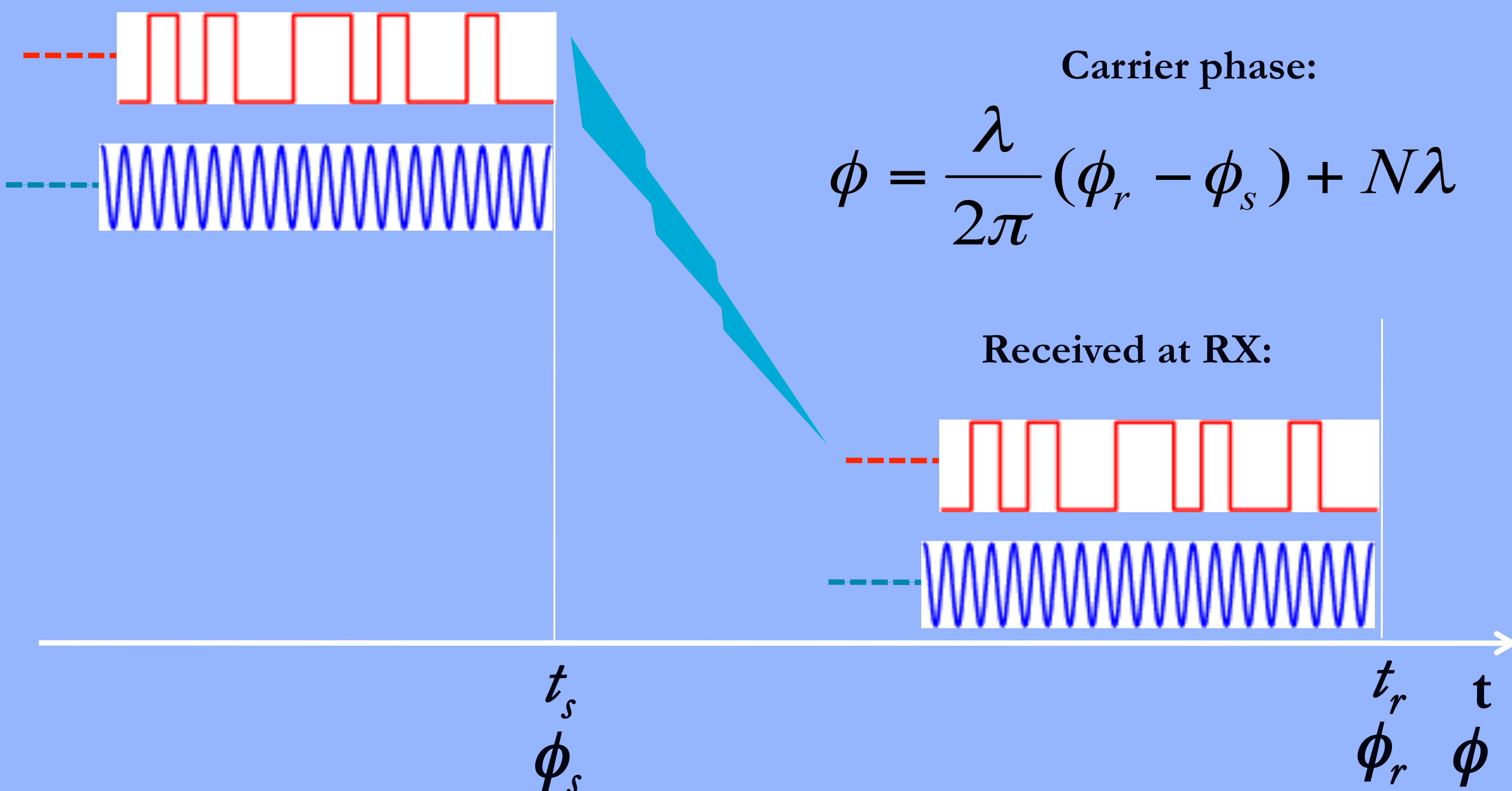
Transmitted at SV:

Pseudorange:

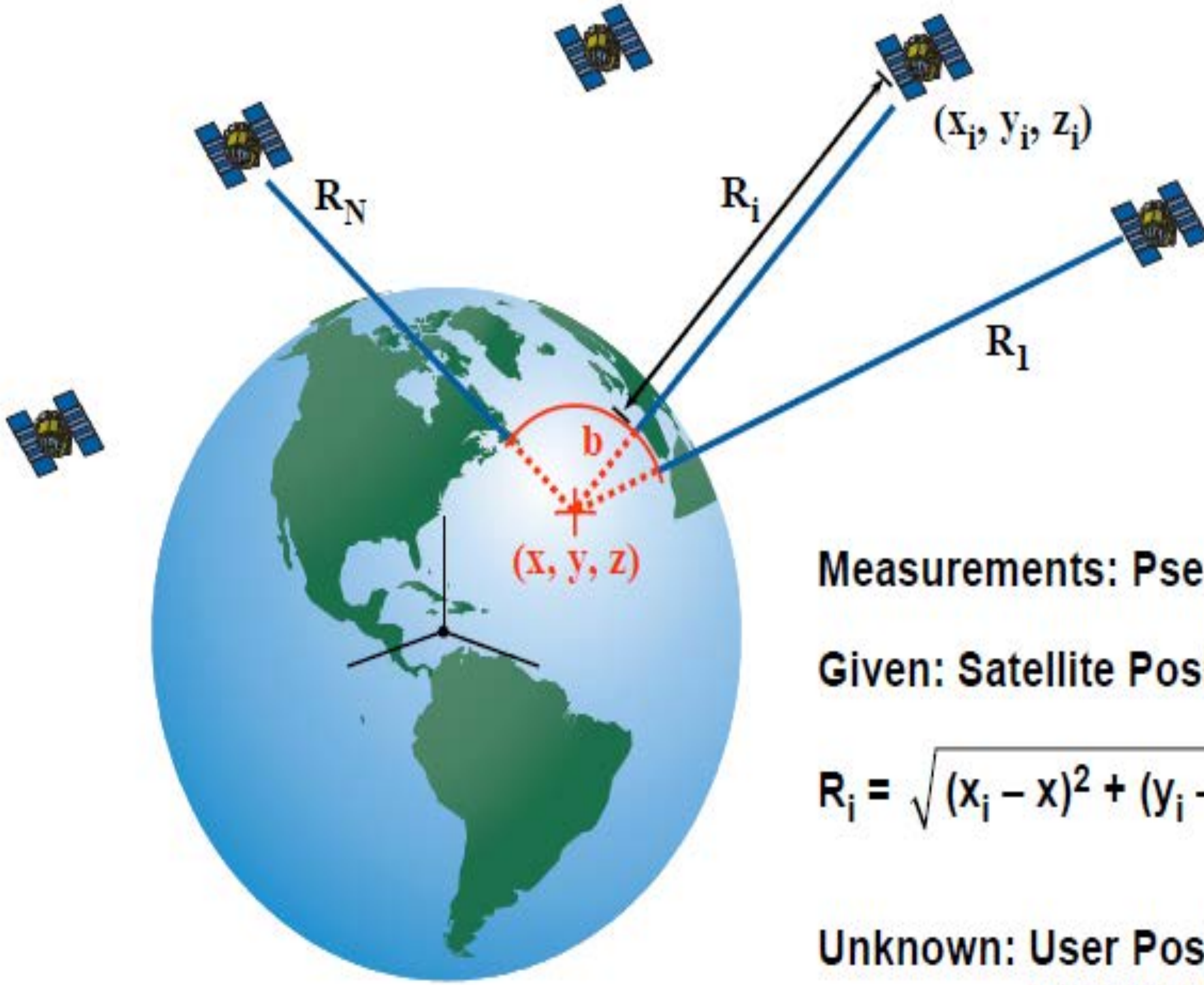
$$\rho = c(t_r - t_s)$$

Carrier phase:

$$\phi = \frac{\lambda}{2\pi}(\phi_r - \phi_s) + N\lambda$$



GPS Positioning



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

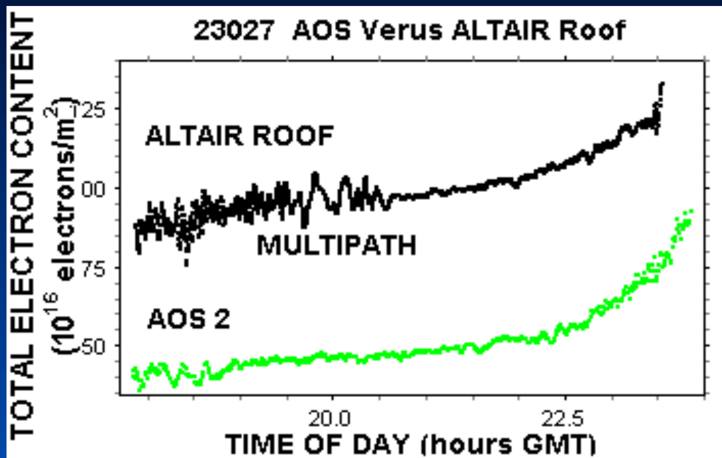
Measurements: Pseudoranges $\{R_i\}$

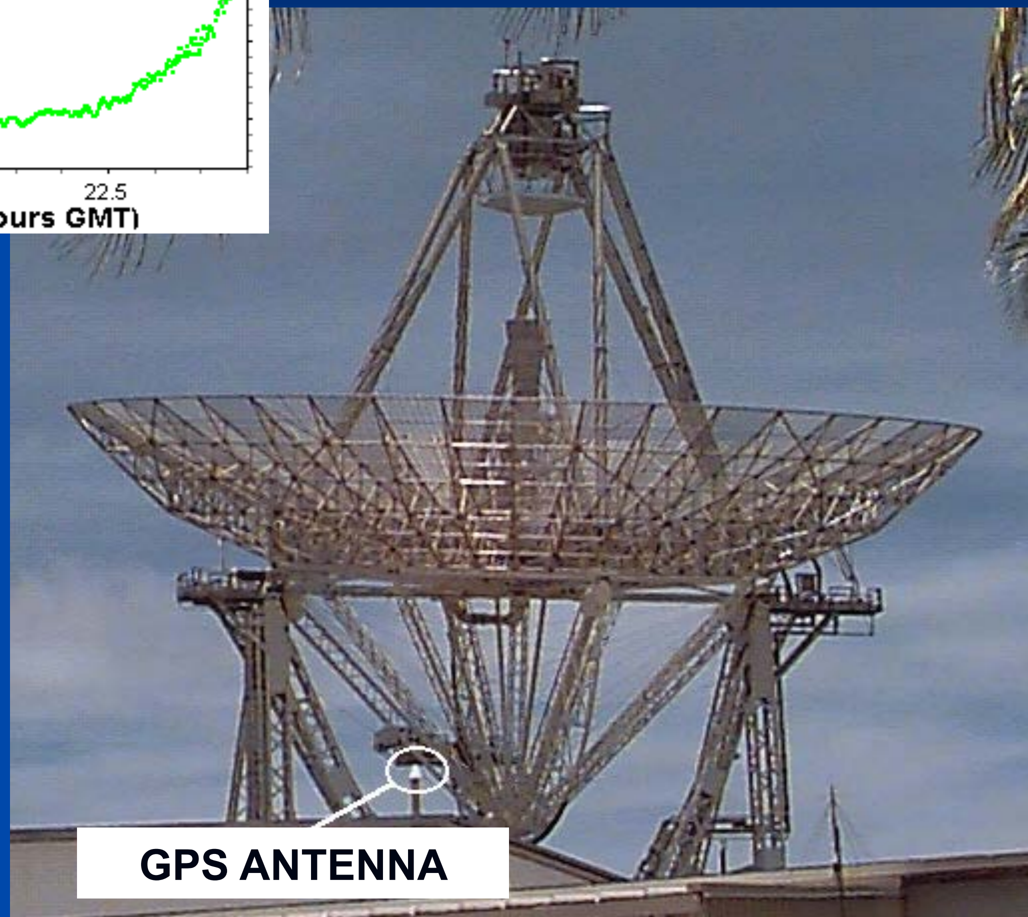
Given: Satellite Positions $\{(x_i, y_i, z_i)\}$

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

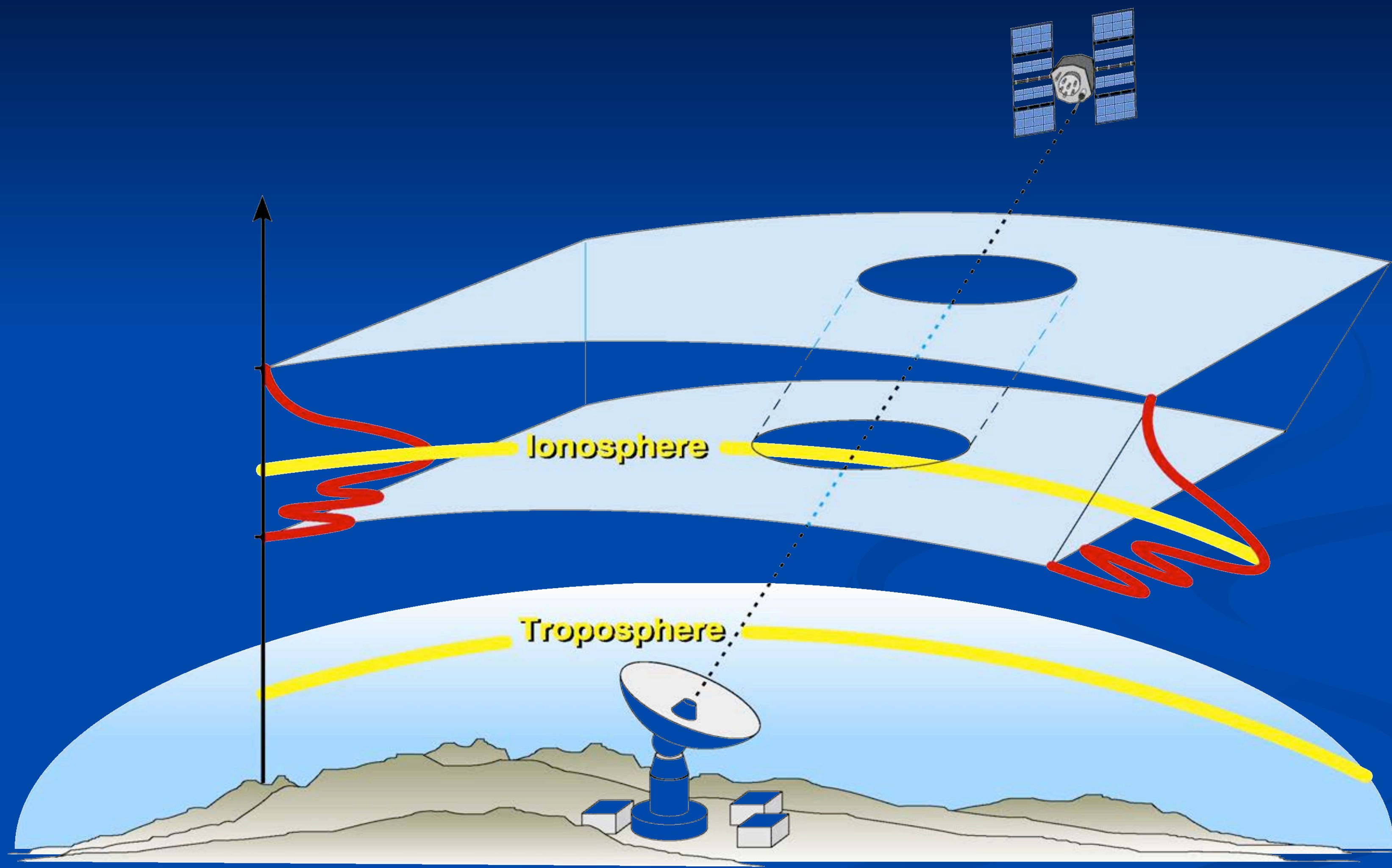
Unknown: User Position (x, y, z)
Receiver Clock Bias b

GPS Signal Multipath



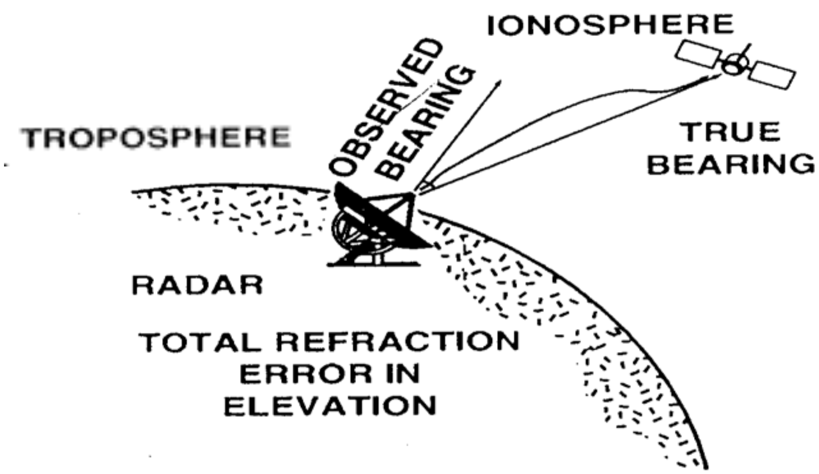


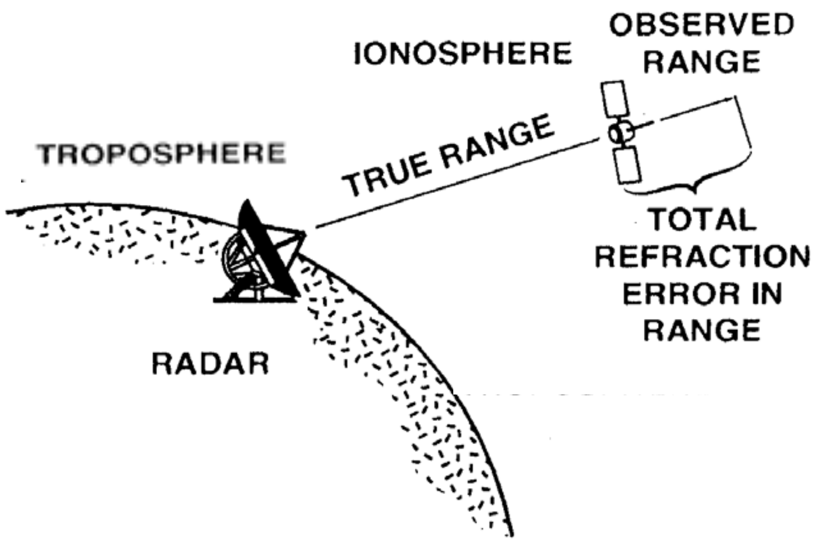
Atmospheric Propagation



From Attila Komjathy, JPL

Illustration of Atmospheric Effects





Index of Refraction in the Ionosphere

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

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

ω = the angular frequency of the radar wave,

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

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

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

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

e = electronic charge, m_e = electron mass,

and ε_0 = permittivity constant.

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

Ionospheric Parameters GPS can be used to measure

Ground-Based Receivers

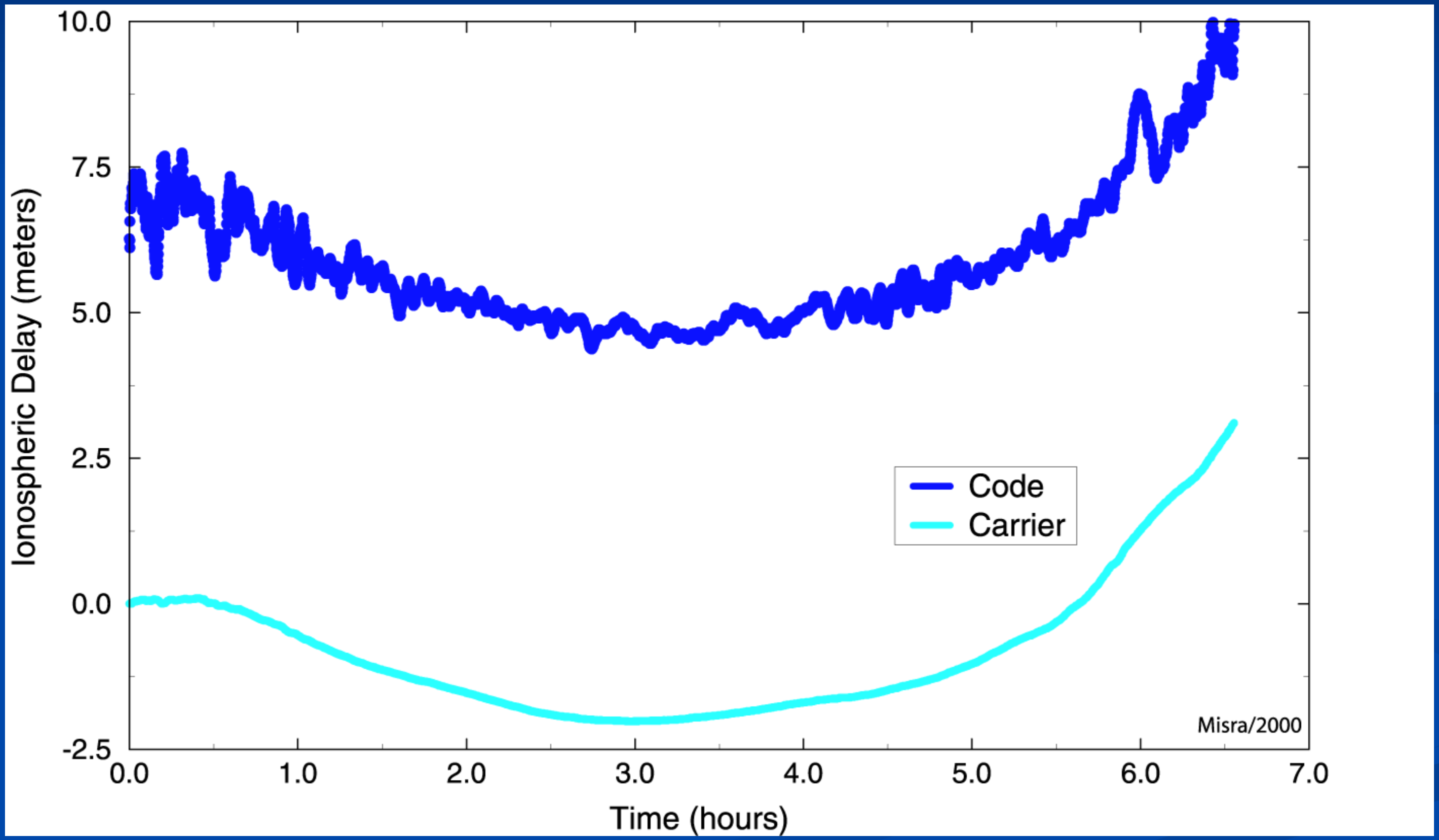
- Total Electron Content
- Scintillation Parameters: S_4 and σ_Φ

Space-Based Receivers

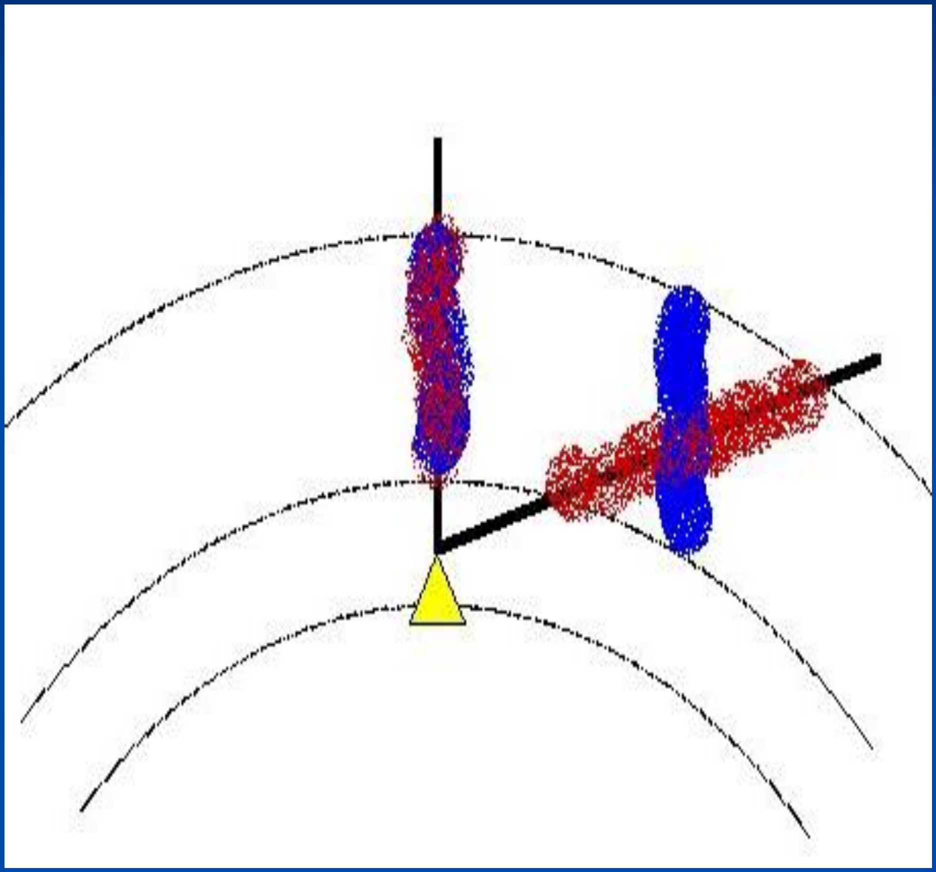
- Electron Density Profiles
- Scintillation Parameters: S_4 and σ_Φ

Total Electron Content (TEC) Estimation

Dual-Frequency Measurements



Problem 1: Mapping Function

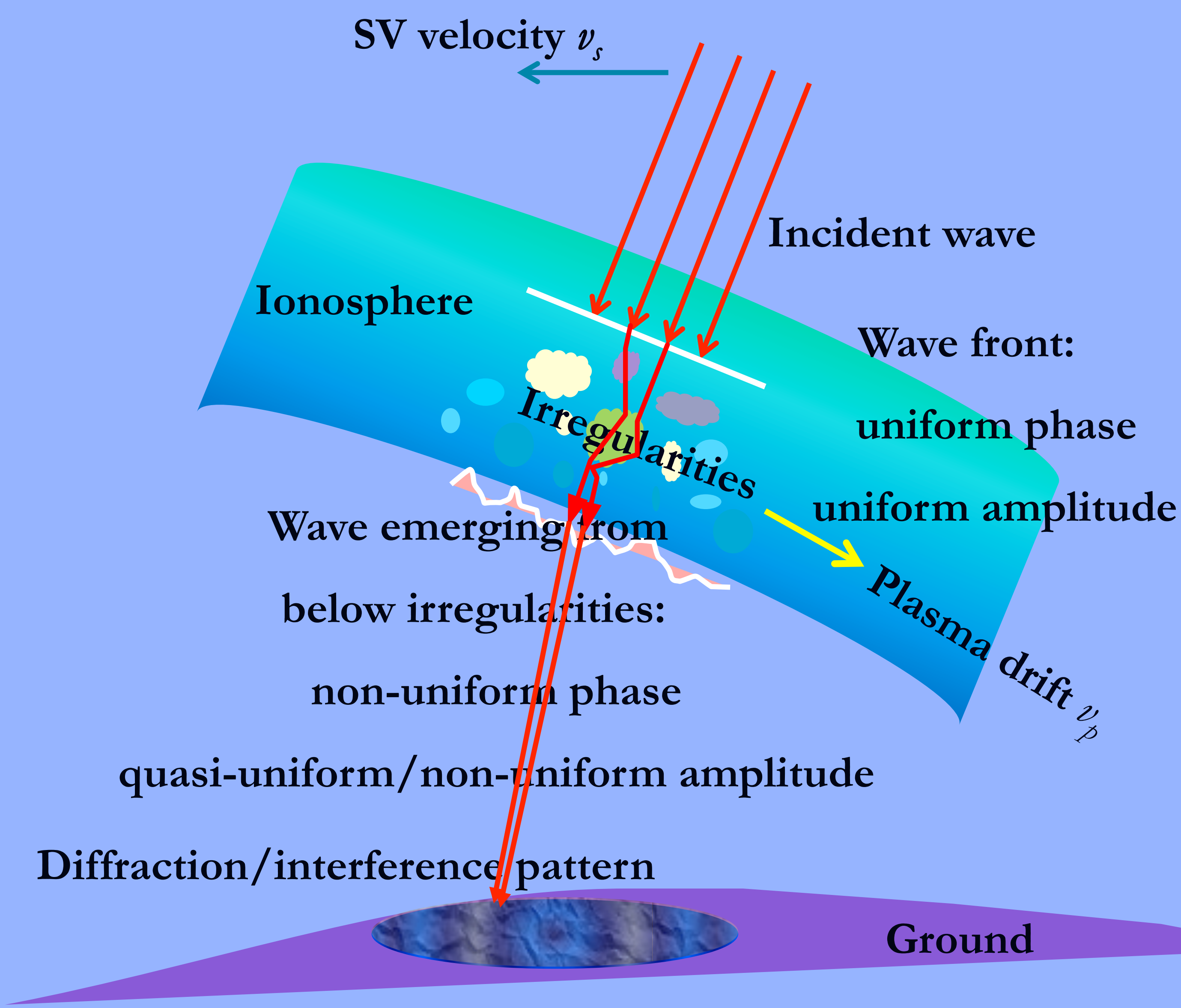


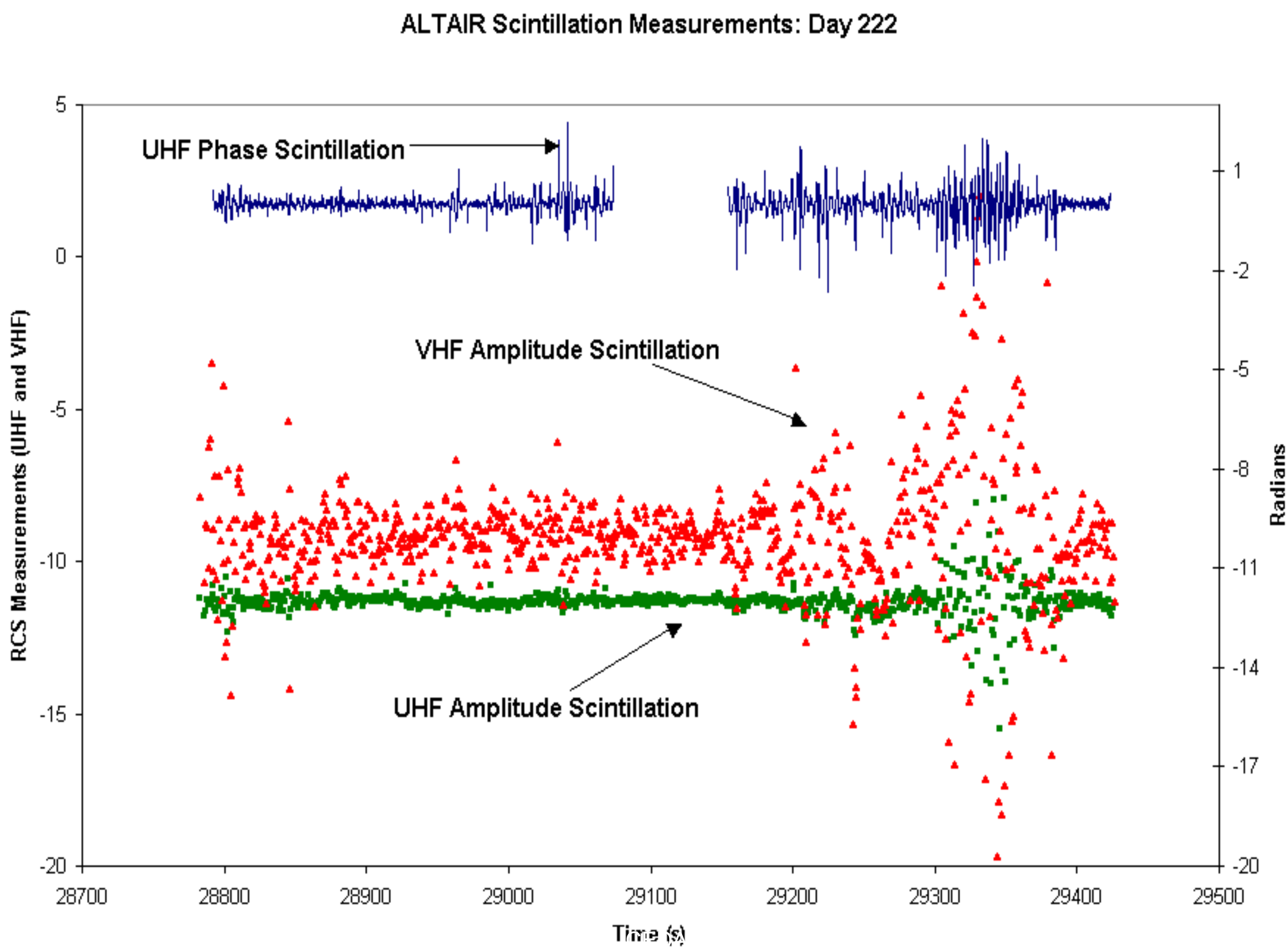
- Mapping function used to map TEC (line of sight) to Vertical TEC
- Assigns V-TEC to pierce point
- Function of Elevation Range: 1 < Z < 3

Problem 2: GPS Biases

- GPS delay difference between two frequencies provides TEC
- Delay differences are also introduced by the satellite and receiver
- Satellite biases are determined by IGS community and are fairly stable
- Receiver biases are determined by individual user and most users estimate one bias over a 24 - hour period.

Ionosphere Scintillation Conceptual Description





ALTAIR Scintillation Measurements: Day 222
UHF Phase Scintillation
VHF Amplitude Scintillation
UHF Amplitude Scintillation
RCS Measurements (UHF and VHF)
Radians
Time (s)
5
0
-5
-10
-15
-20
1
-2
-5
-8
-11
-14
-17
-20
28700
28800
28900
29000
29100
29200
29300
29400
29500

Ascension Island Data Processing

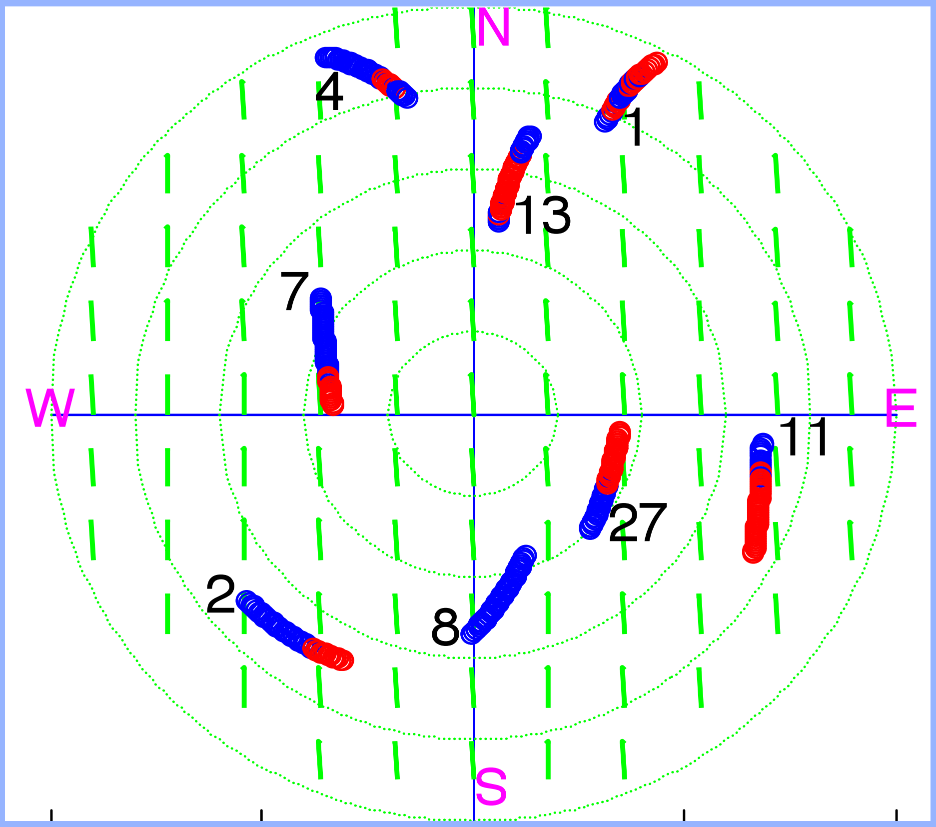
Lat: S7 °55' 20”

Lon: W14° 25' 30”
3/18/2001, 8:45-9:30PM

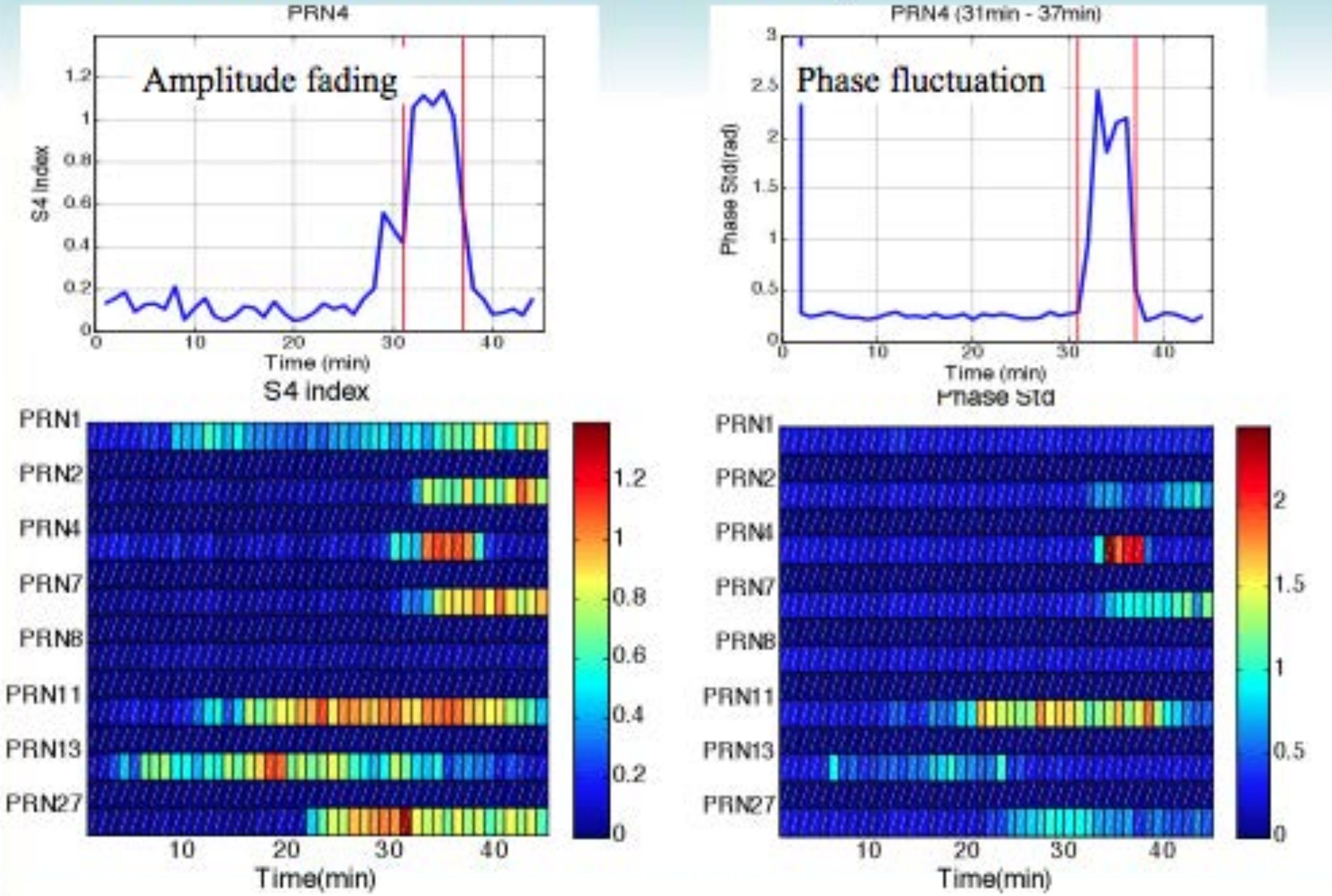
AFRL Hanscom, Ted Beach

NAVSYS DSR-100

f_s =2MHz , 1 bit resolution, f_{IF} = 309kHz



Scintillation Indices: S_4 and σ_ϕ

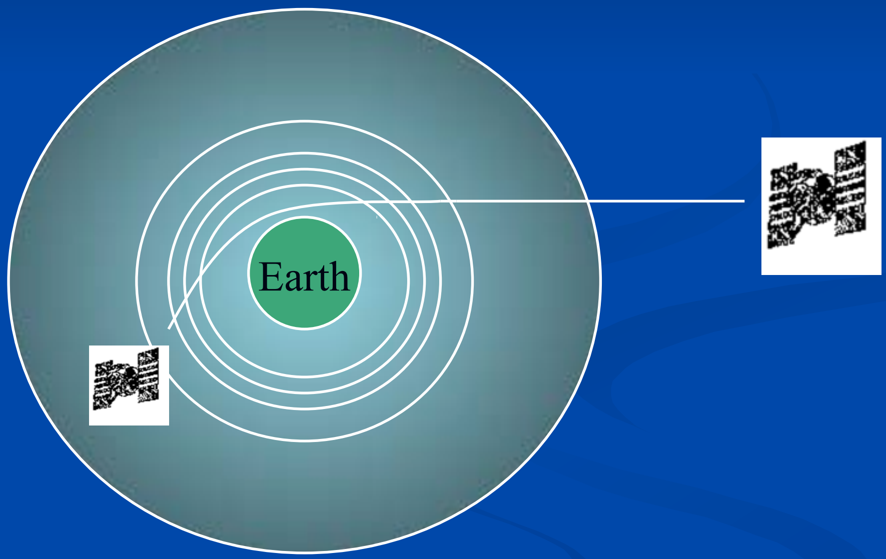


GPS Occultation

Typical occultation event last 1-2 min, beginning with the signal path passing through the mesopause and ending with it grazing the Earth's limb.

Orbit Altitudes :

LEO Satellite = 775 km

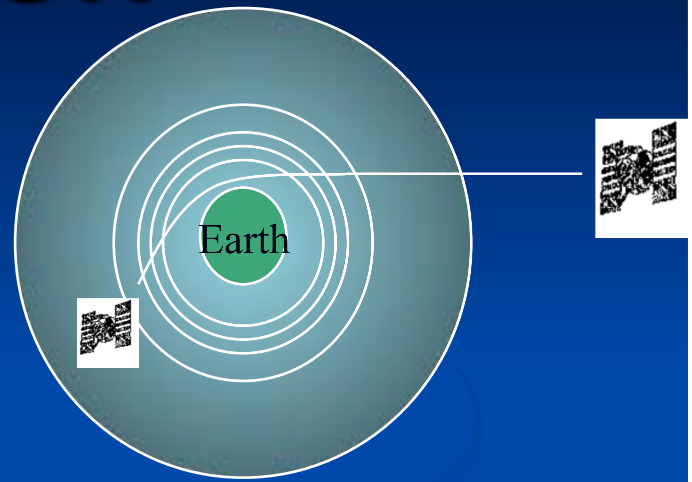


LEO Satellite

Occulted GPS Satellite

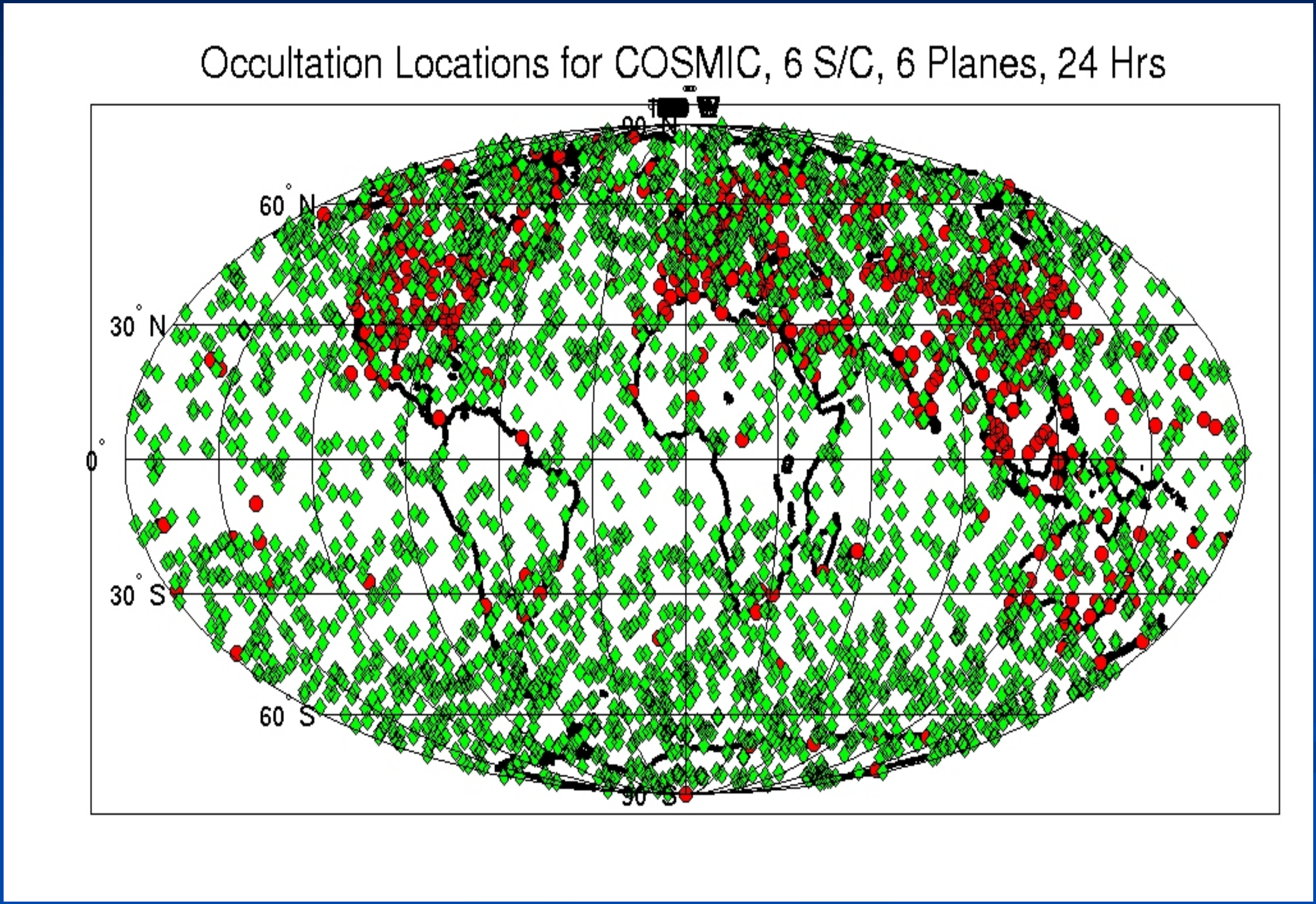
OCCULTATION

Received GPS frequency can be measured to an accuracy on the order of one part in 10^{13}. This translates to a bending accuracy of about 1 microdegree.

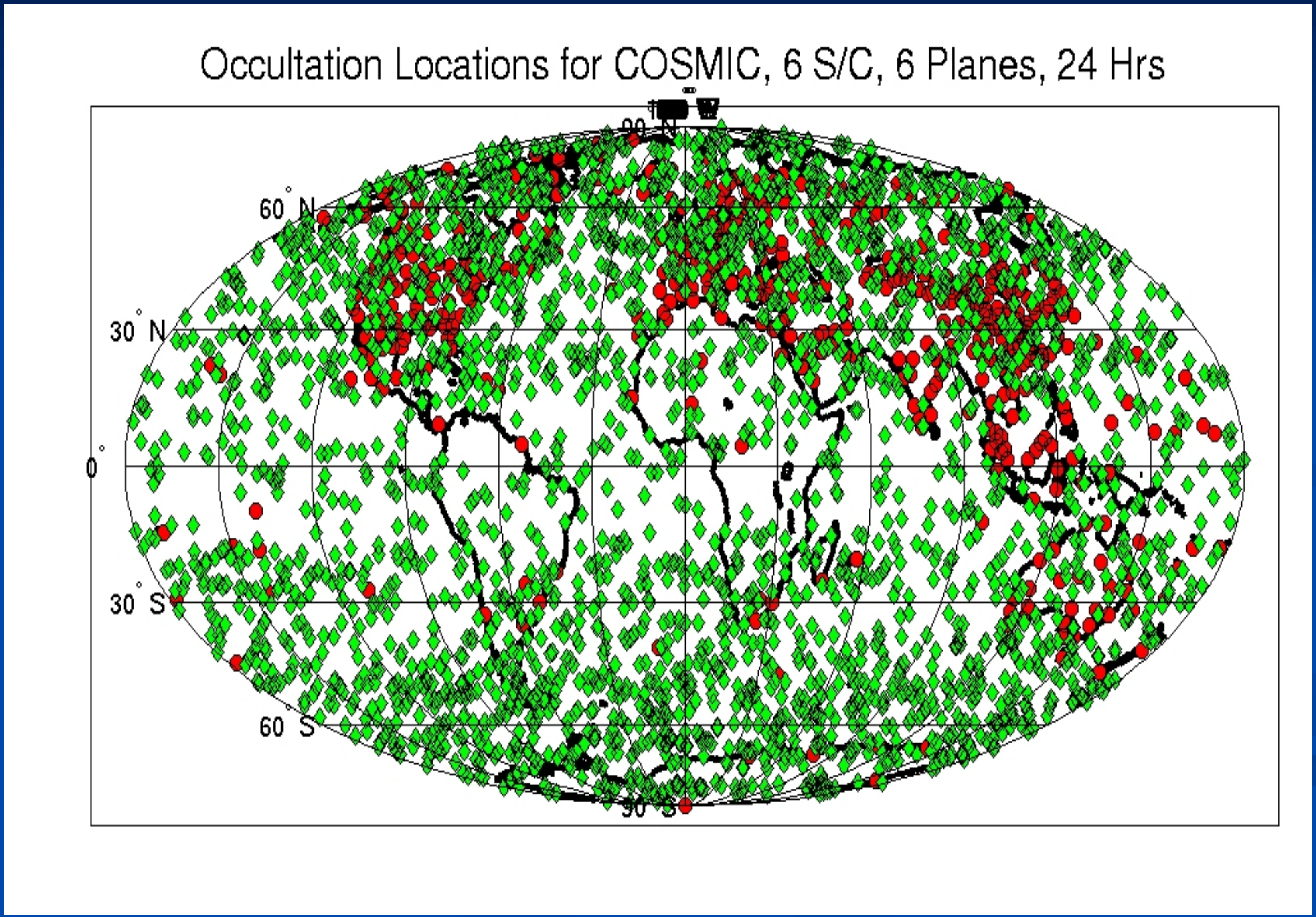


- **The measurement is the integrated effect of the bending caused by the atmosphere --- The vertical distribution of refractivity is the desired quantity.**
- **The ABEL transform is used to invert integral measurements to vertical quantities.**

COSMIC sounding distribution in a day



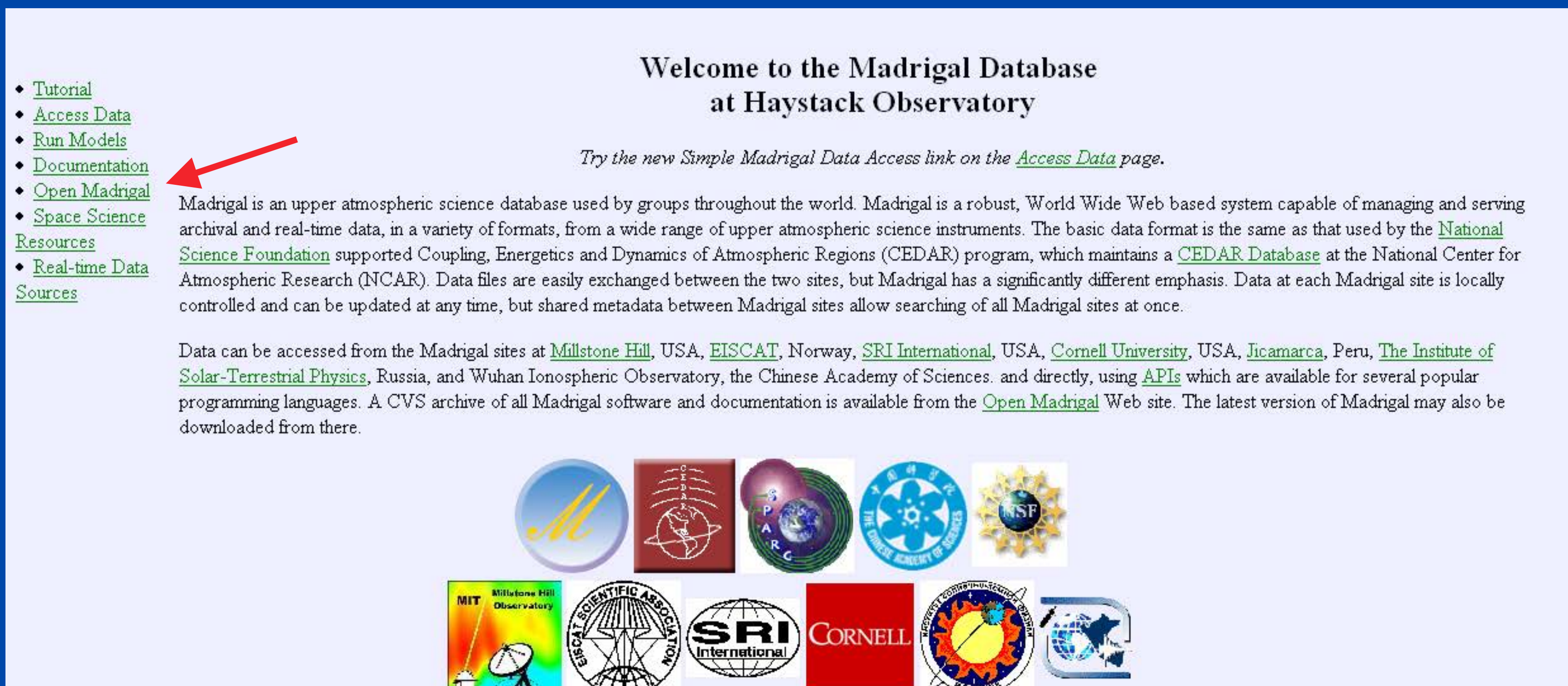
http://cosmic-io-cosmic.ucar.edu/cdaac/index.html



Madrigal Data Base

www.haystack.mit.edu

- **Madrigal Database provides estimates of vertical TEC in 1 X 1 degree bins every 5 min where data exists.**
- **Currently ~10 years of TEC data from 2000-2005 on-line**



- Tutorial
- Access Data
- Run Models
- Documentation
- Open Madrigal
- Space Science Resources
- Real-time Data Sources

Welcome to the Madrigal Database
at Haystack Observatory

Try the new Simple Madrigal Data Access link on the Access Data page.

Madrigal is an upper atmospheric science database used by groups throughout the world. Madrigal is a robust, World Wide Web based system capable of managing and serving archival and real-time data, in a variety of formats, from a wide range of upper atmospheric science instruments. The basic data format is the same as that used by the National Science Foundation supported Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) program, which maintains a CEDAR Database at the National Center for Atmospheric Research (NCAR). Data files are easily exchanged between the two sites, but Madrigal has a significantly different emphasis. Data at each Madrigal site is locally controlled and can be updated at any time, but shared metadata between Madrigal sites allow searching of all Madrigal sites at once.

Data can be accessed from the Madrigal sites at Millstone Hill, USA, EISCAT, Norway, SRI International, USA, Cornell University, USA, Jicamarca, Peru, The Institute of Solar-Terrestrial Physics, Russia, and Wuhan Ionospheric Observatory, the Chinese Academy of Sciences. and directly, using APIs which are available for several popular programming languages. A CVS archive of all Madrigal software and documentation is available from the Open Madrigal Web site. The latest version of Madrigal may also be downloaded from there.

Outline

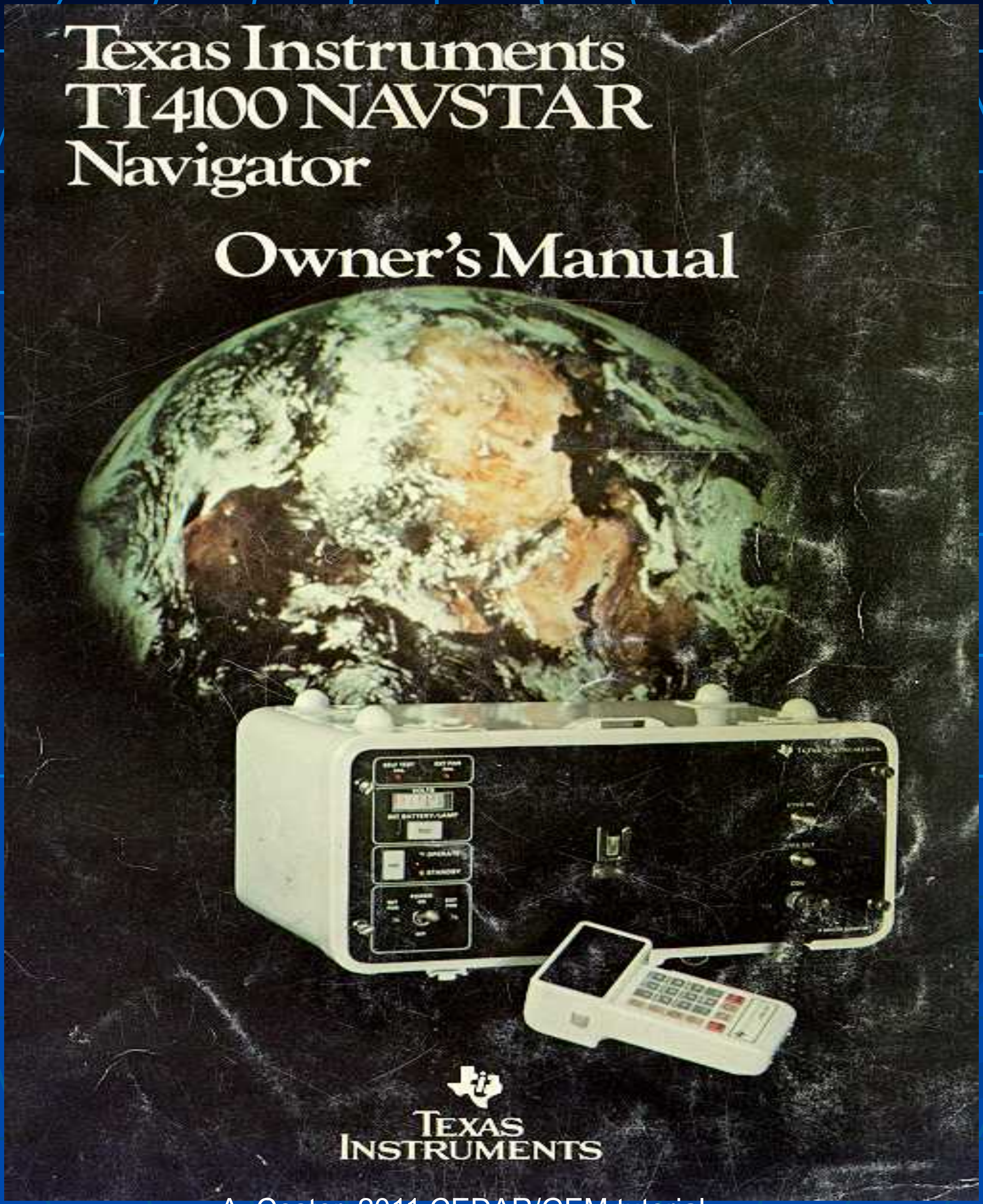
ABC's of GPS

History (some) of measuring the ionosphere with GPS

IT Coupling – GPS

MI Coupling – GPS

What's on the horizon

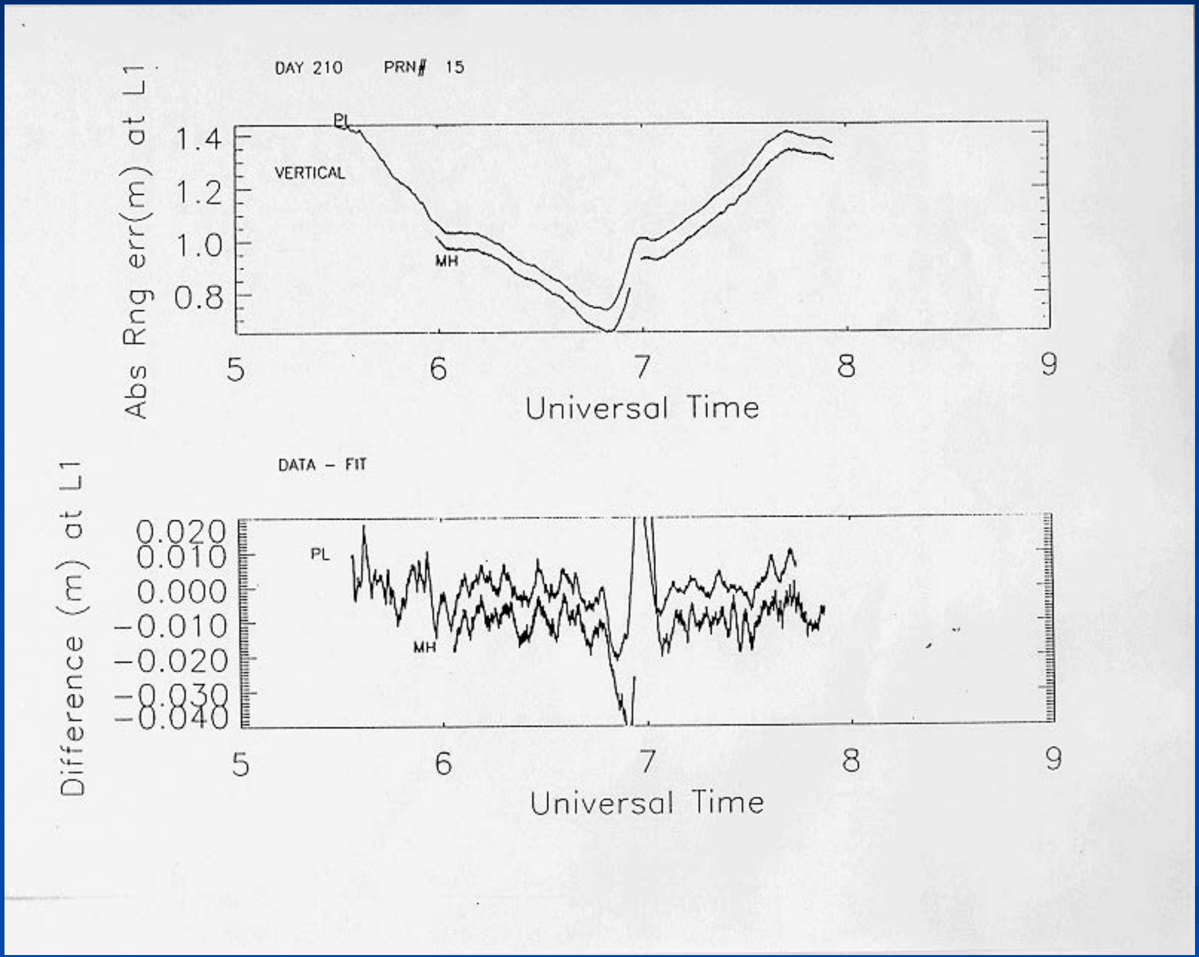

Texas Instruments
TI 4100 NAVSTAR
Navigator
Owner's Manual
Texas Instruments

27

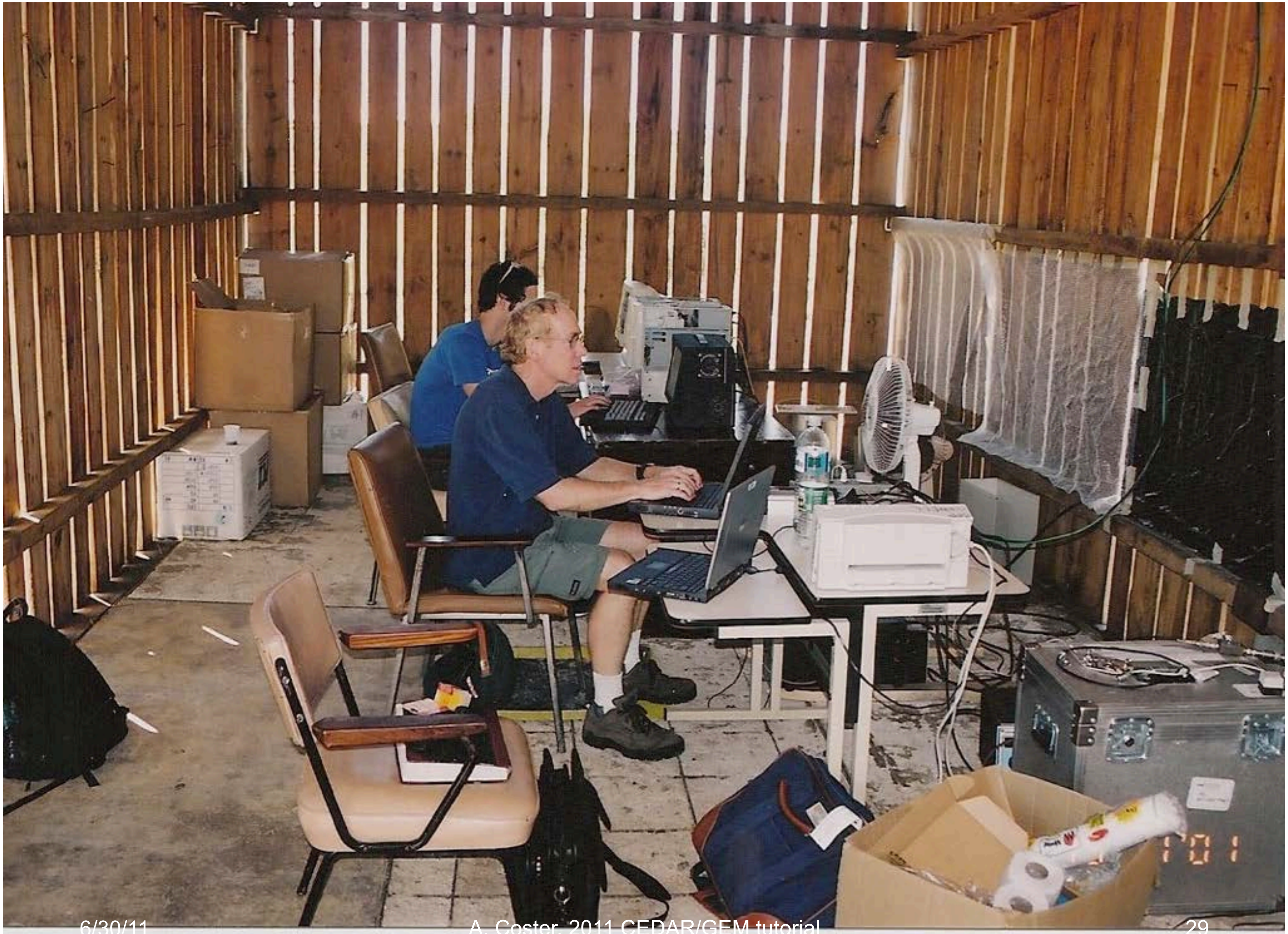
Historical TID Data 29 July 1991

Near Solar Maximum   Geomagnetically Quiet   Local Night

Characteristics of Nighttime MSTID with a 3% TECP



Two TI 4100 receivers separated ~ 25 km in MA P. Doherty and A. Coster



IGS: International GNSS Service

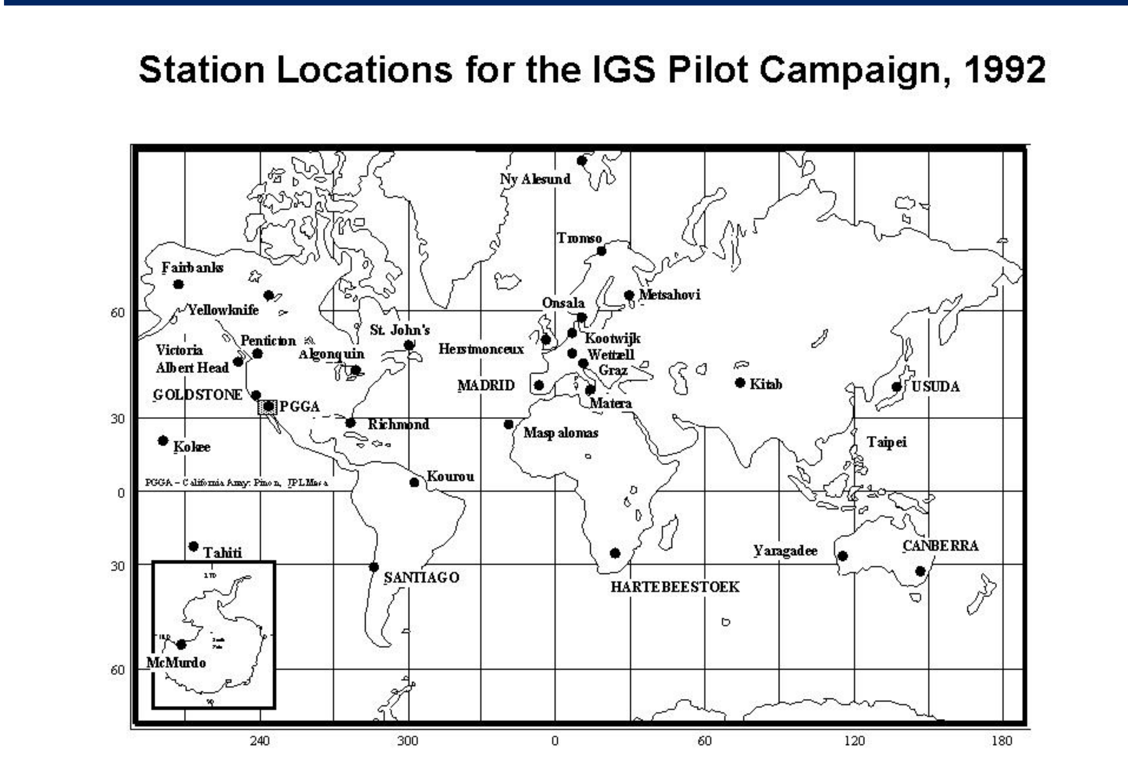
The creation of the IGS was initiated in 1989 and became an official International Association of Geodesy service in 1994.

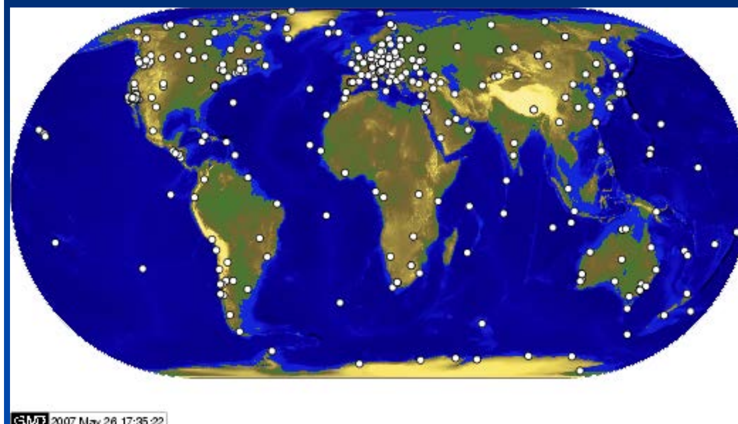
Early user of internet.

Stressed importance of standardized products, freely accessible on the internet.

Since its creation the IGS Central Bureau is located in the USA at JPL with Ruth Neilan as director. Today the IGS truly is an interdisciplinary service in support of Earth Sciences and Society committed to use of the data from all GNSS

IGS Development





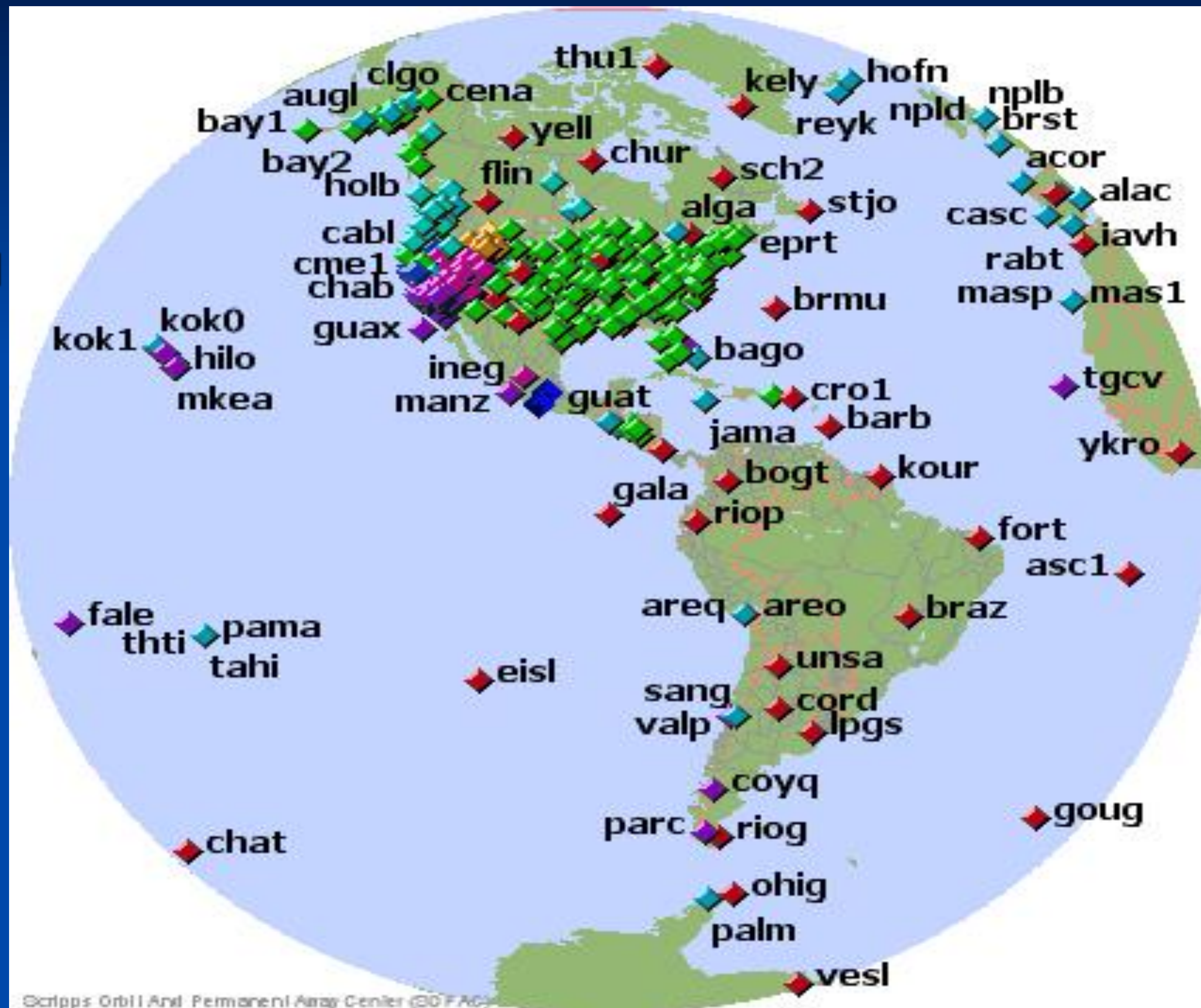
IGS Network in 2007

In 1992 the IGS was based on about 20 geodetic receivers, 400+ receivers are active and their data retrievable today

Based on this data JPL scientists first developed mapping of TEC across the US

Wide Area Distribution of 'Raw' Information

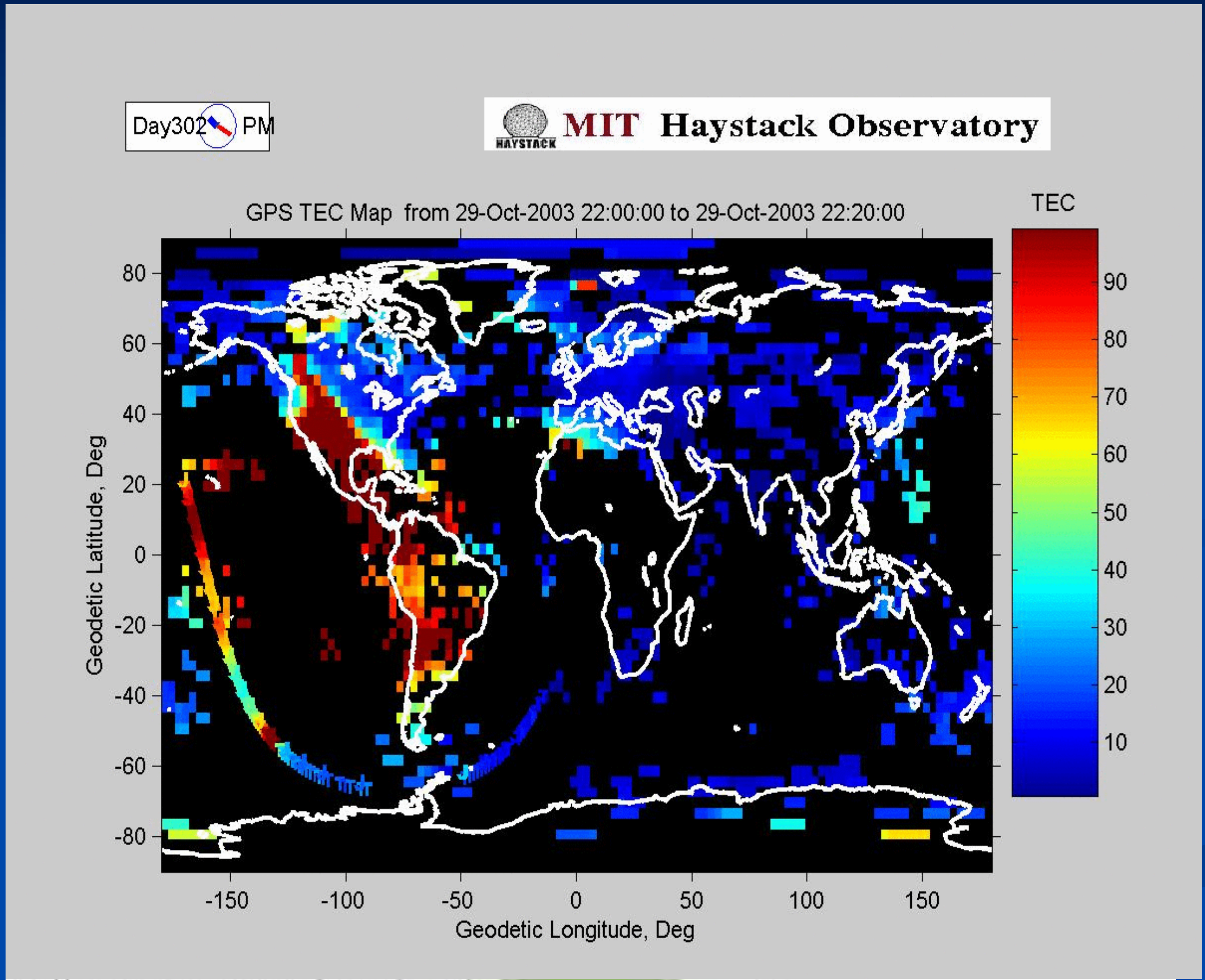
Distributed networks of sensors yield global physics unattainable with single-point measurements



[Coster et al, 2003]

Wide Area Distribution of 'Raw' Information

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

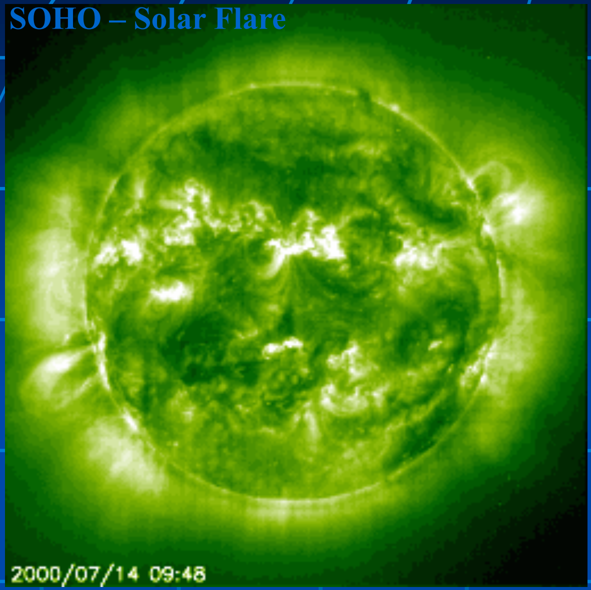


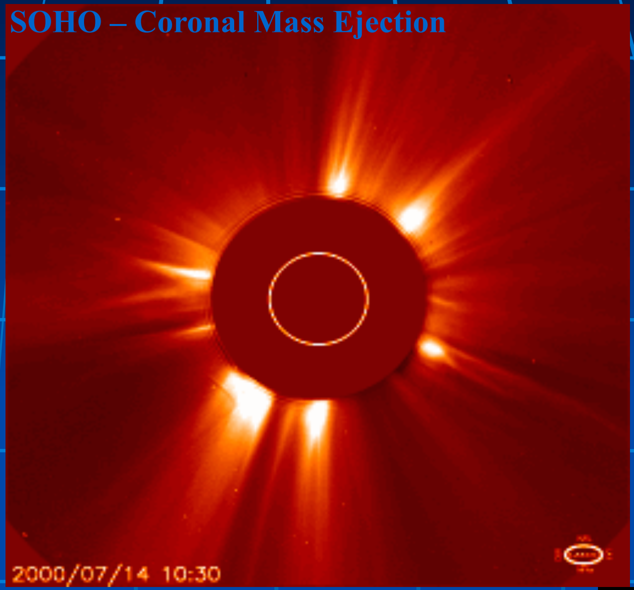
Example :

Global GPS-derived ionospheric mapping during geomagnetic disturbances

[Coster et al, 2003]

Solar Flare of 14 July 2000

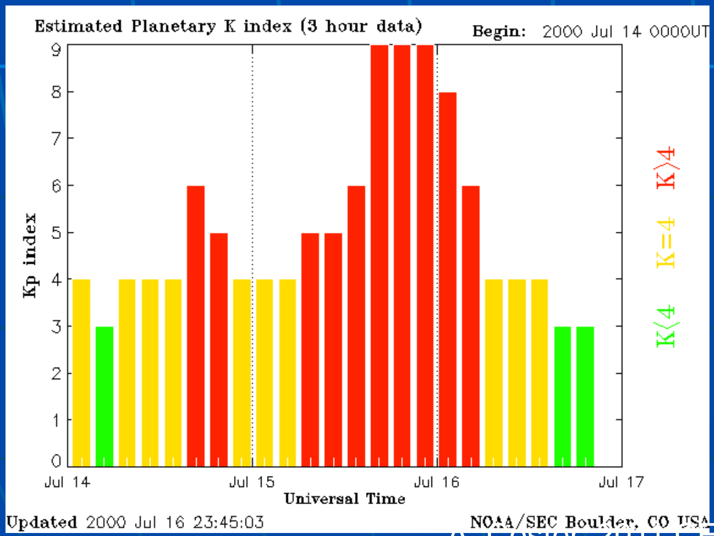


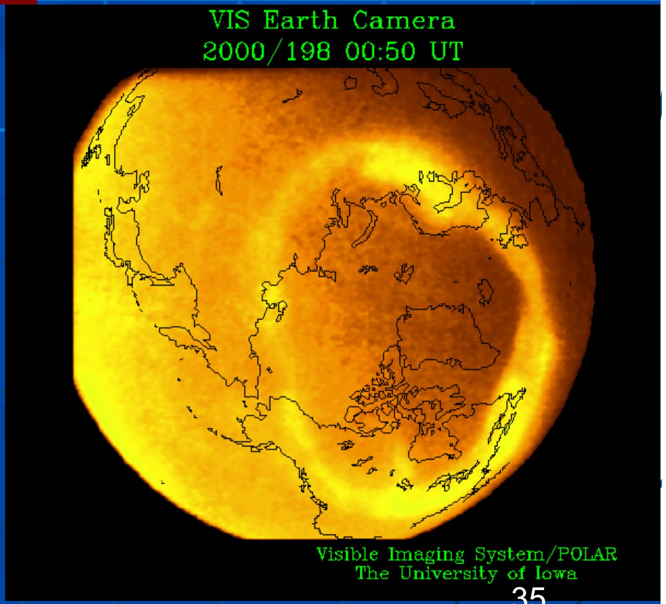


Solar Flare of 14 July 2000

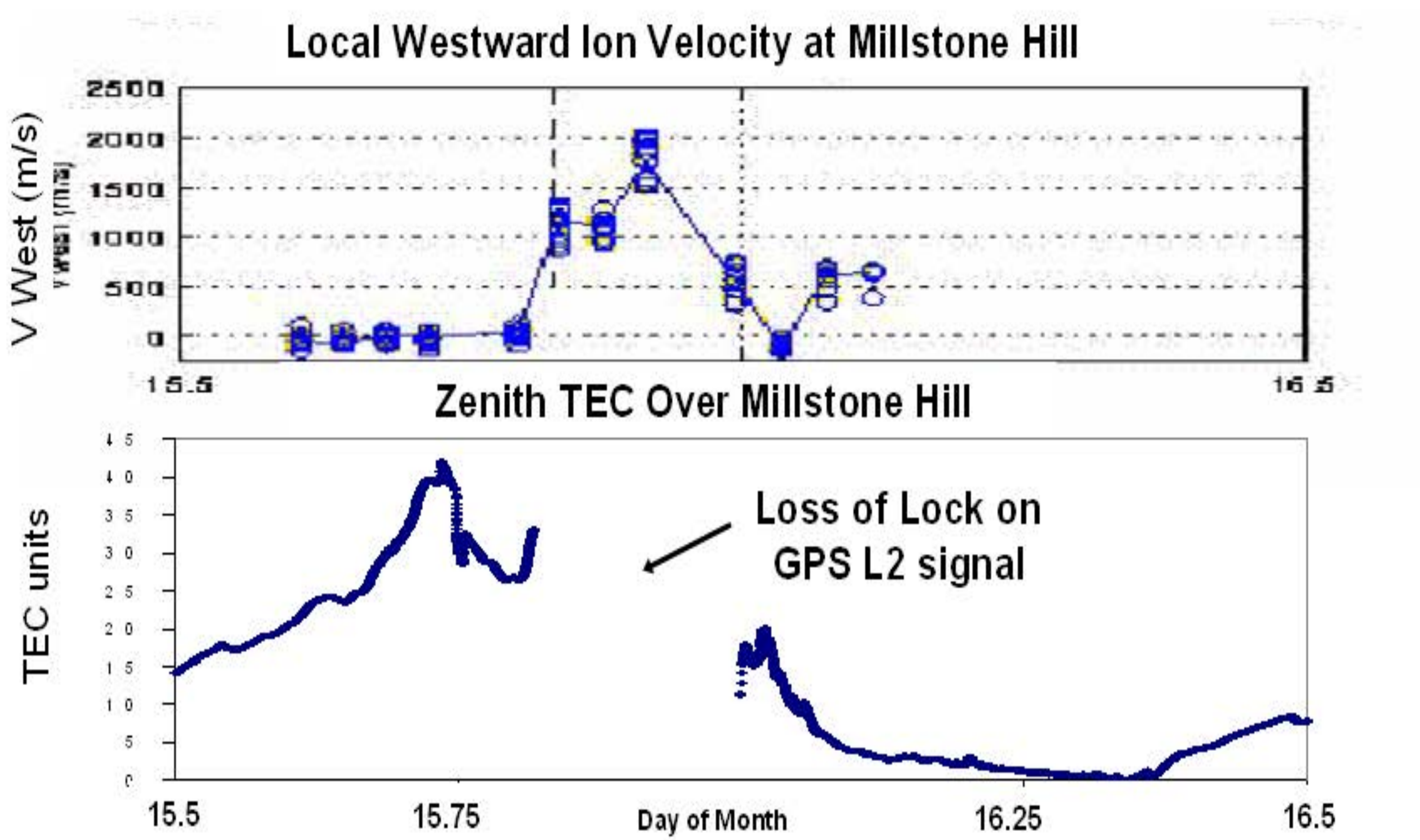
Biggest Solar Storm in Nine Years

Caused very large magnetic storm and ionospheric effects

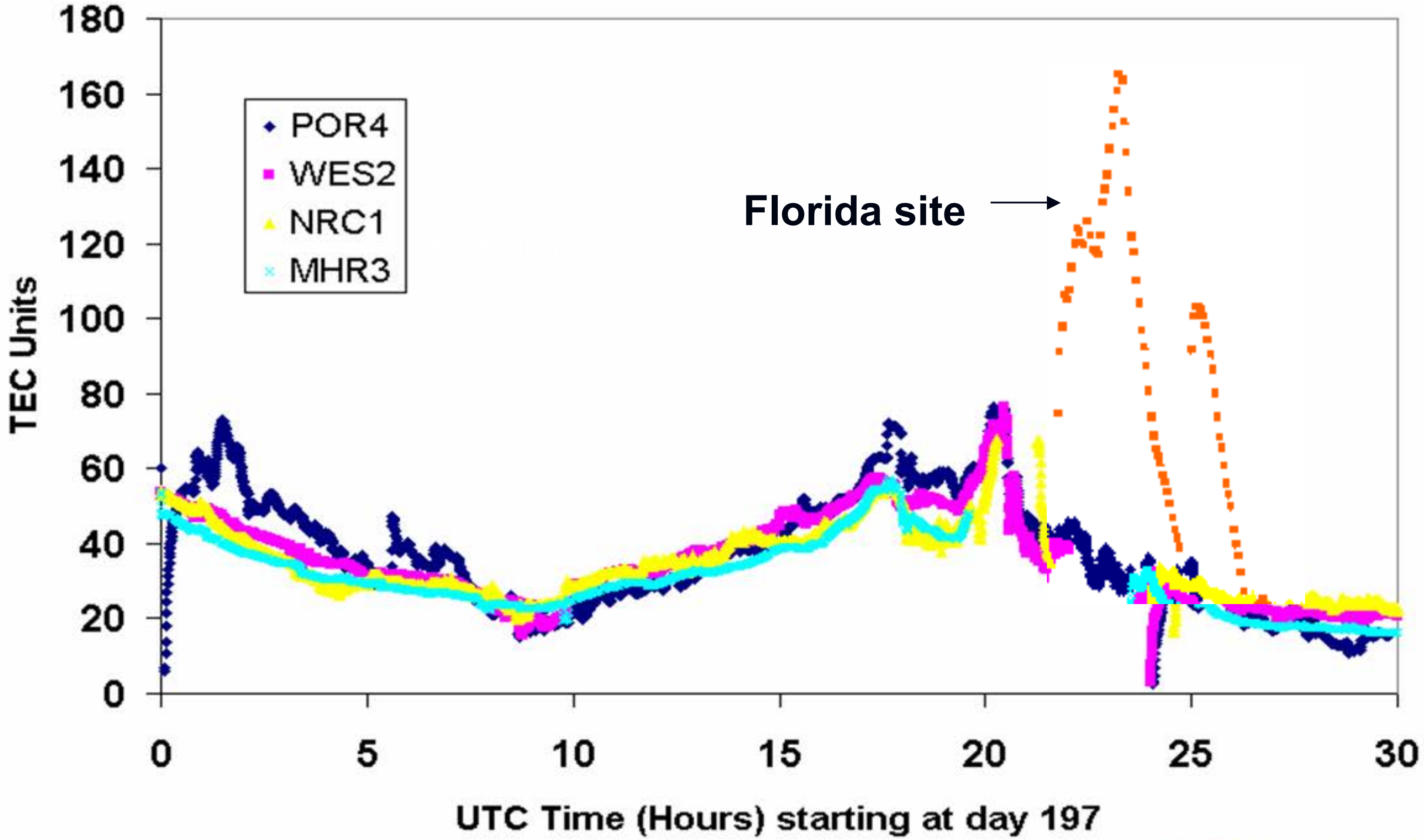




GPS Loss of Lock at Millstone Hill

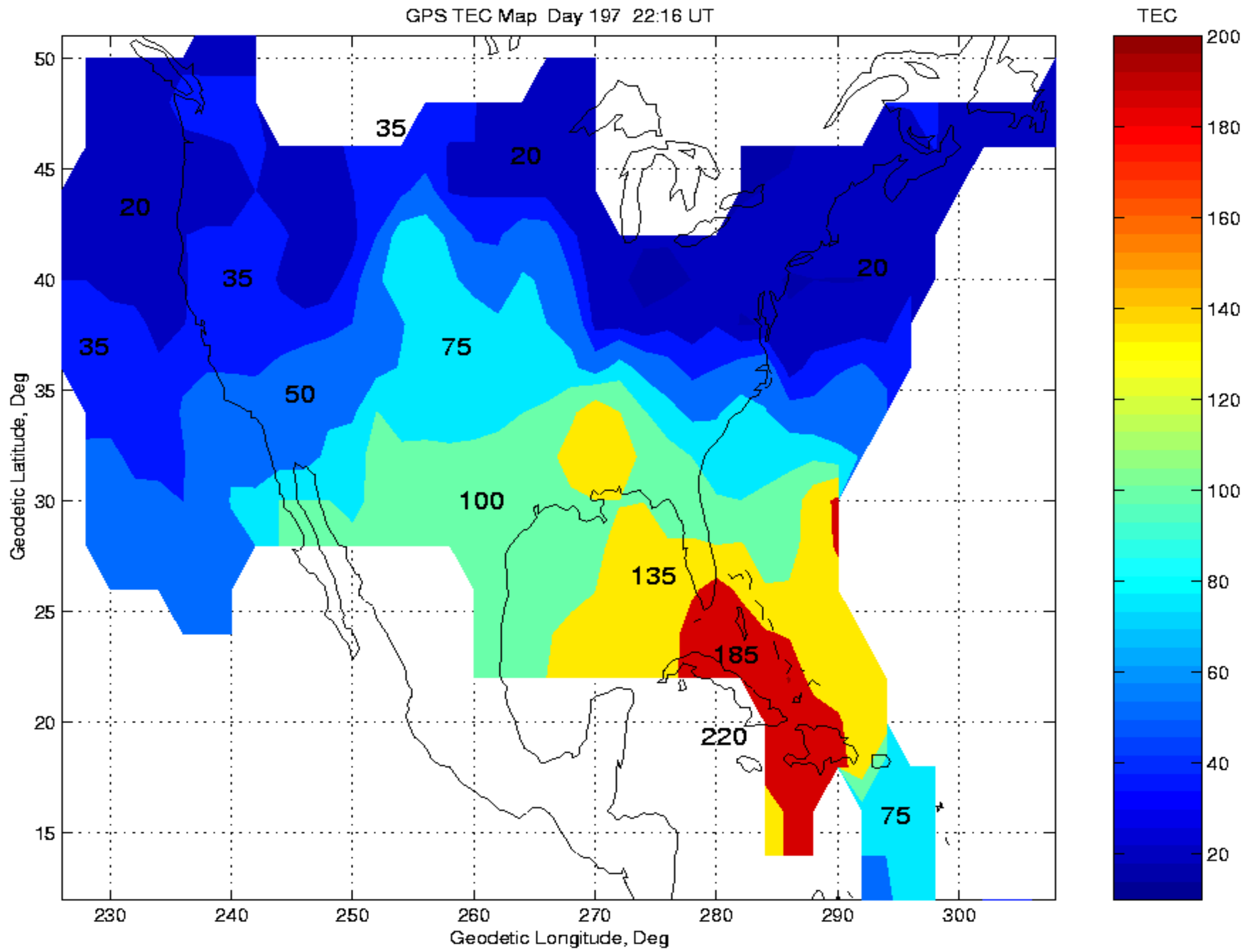


TEC Disturbances on 15 July 2000

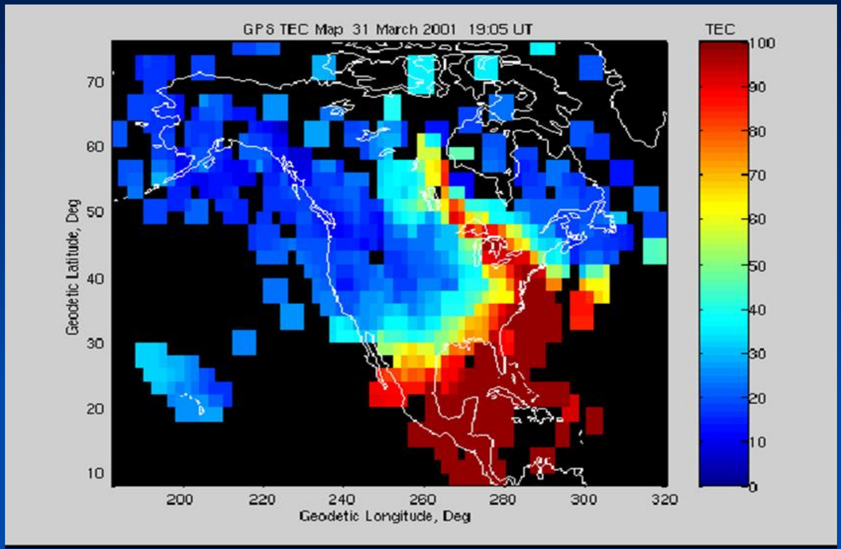


GPS Total Electron Content Map

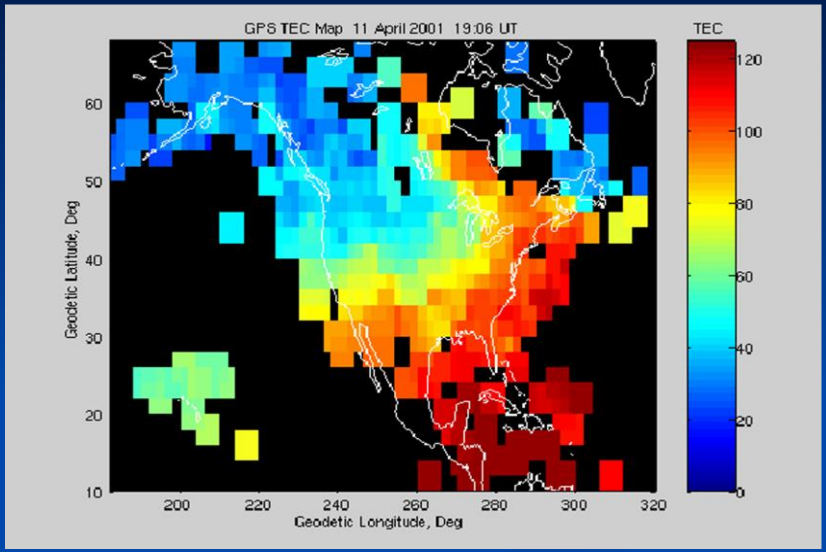
Illustration of Storm Enhanced Density

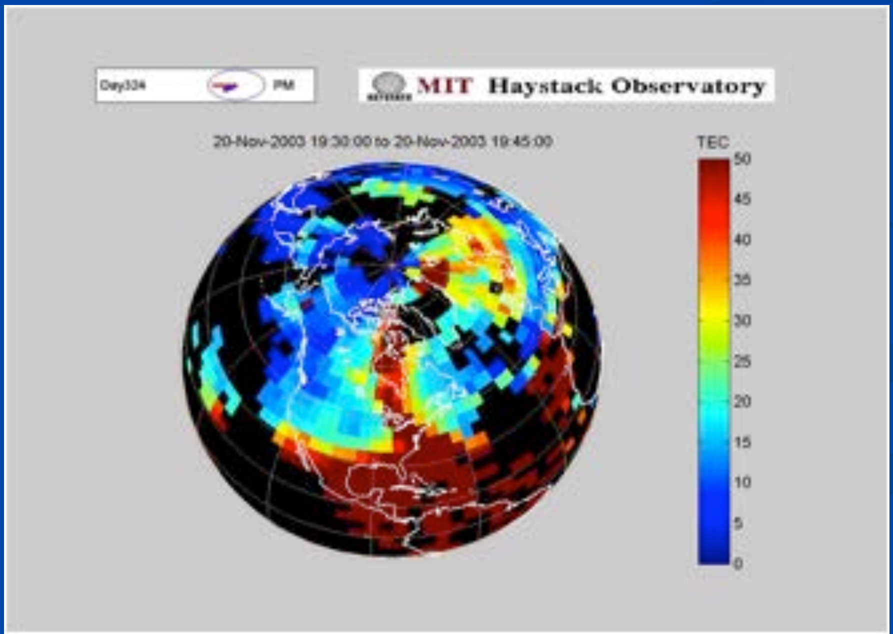


Day 90, 2001

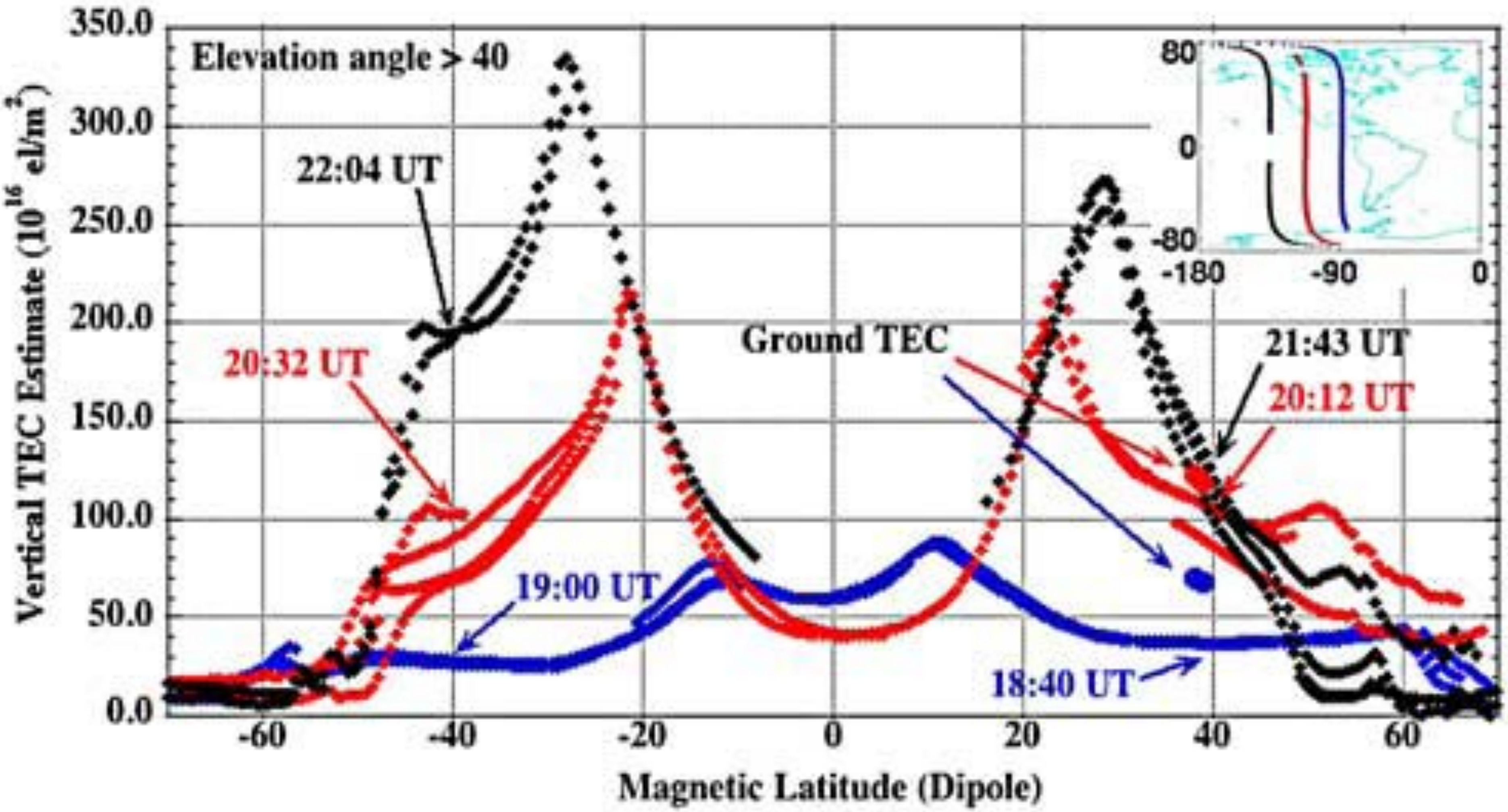


Day 101, 2001



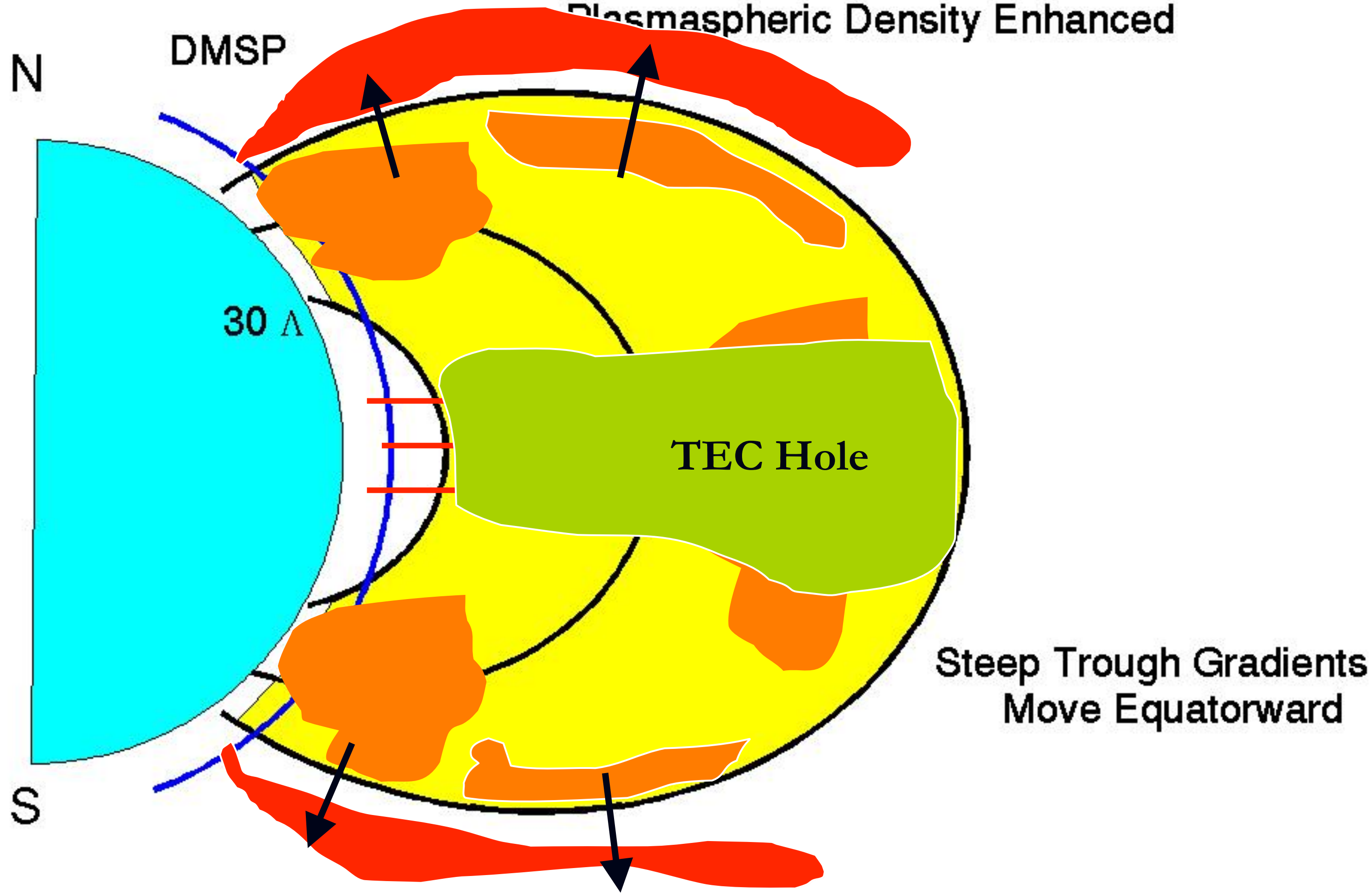


Storm-time Appelton Anomaly



Mannucci et al., 2005, GRL

Effects of Penetration Electric Fields

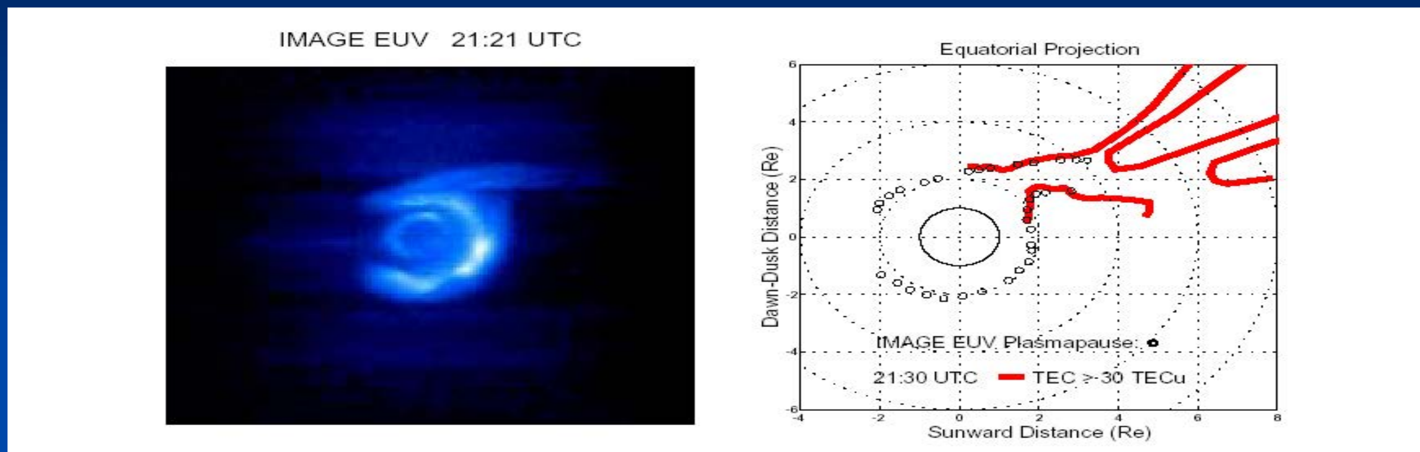


Poleward Electric Field Strips Away Outer Layers of Plasmasphere

Courtesy of J. Foster

Plasmaspheric Tails and Storm Enhanced Density

Foster et al., 2002, GRL



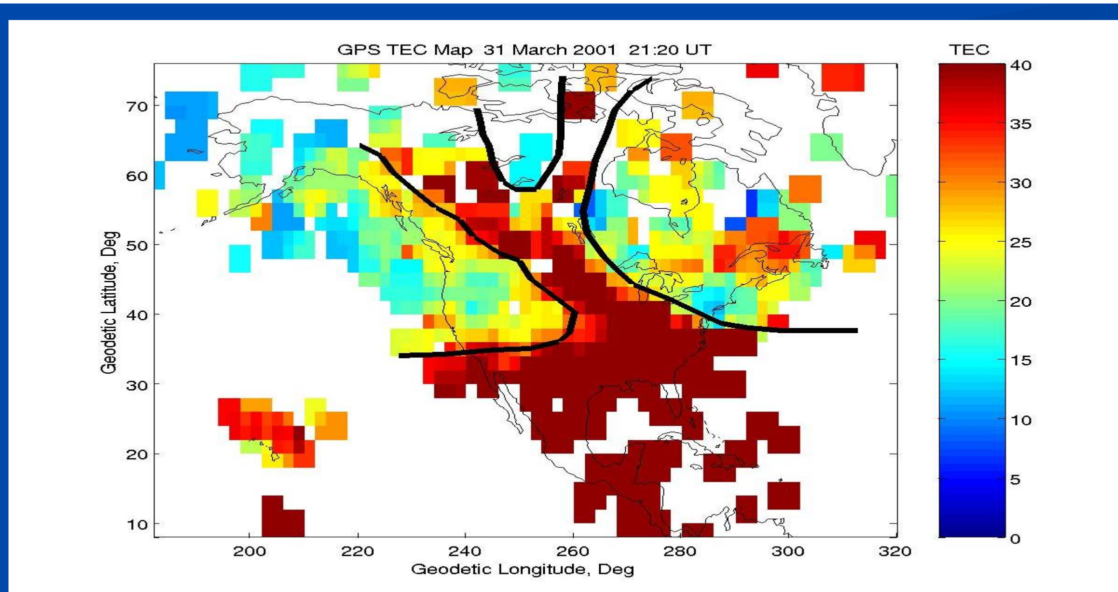
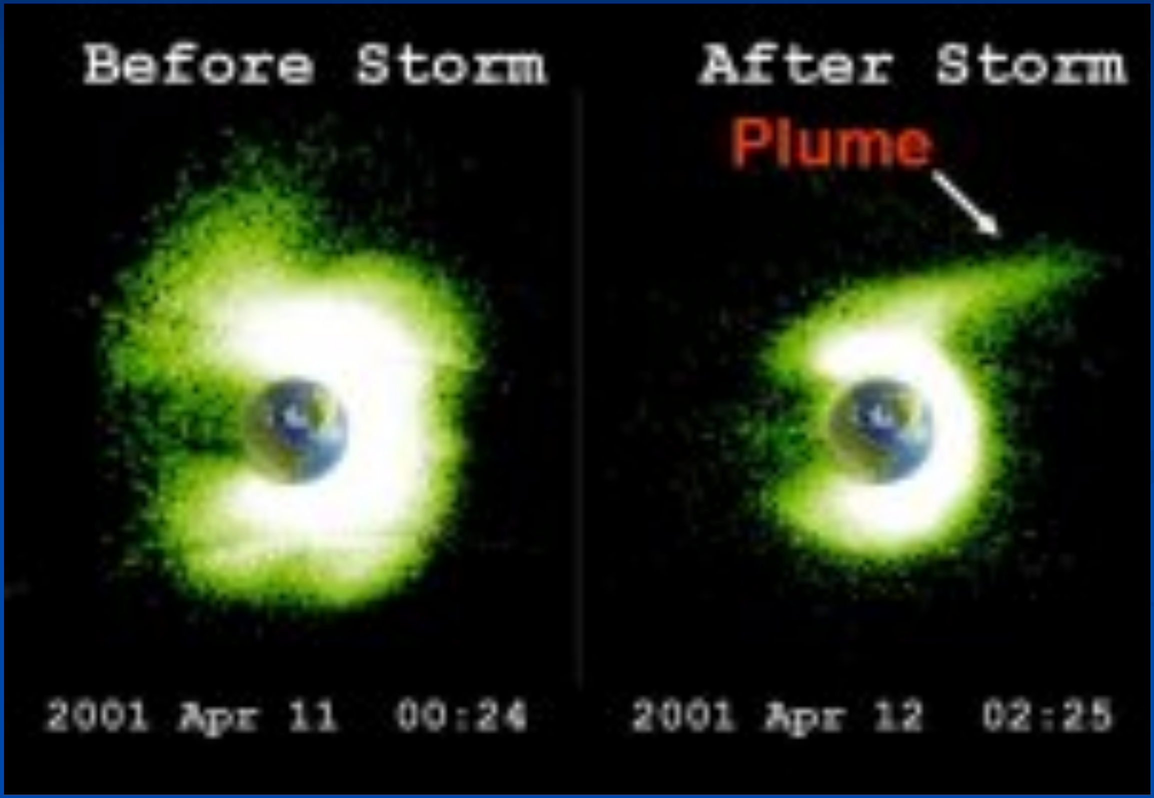
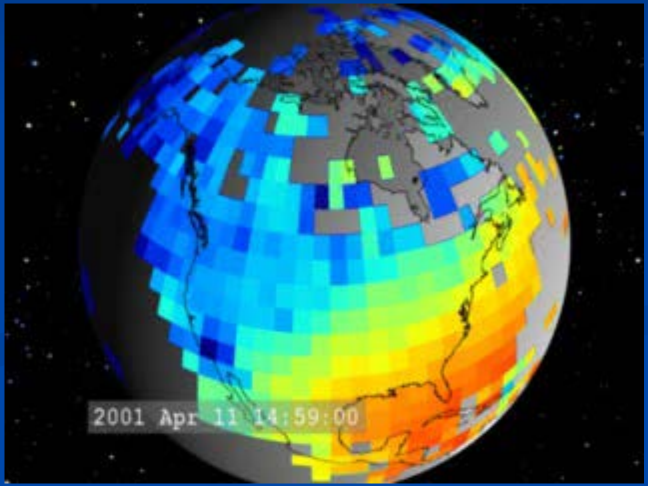
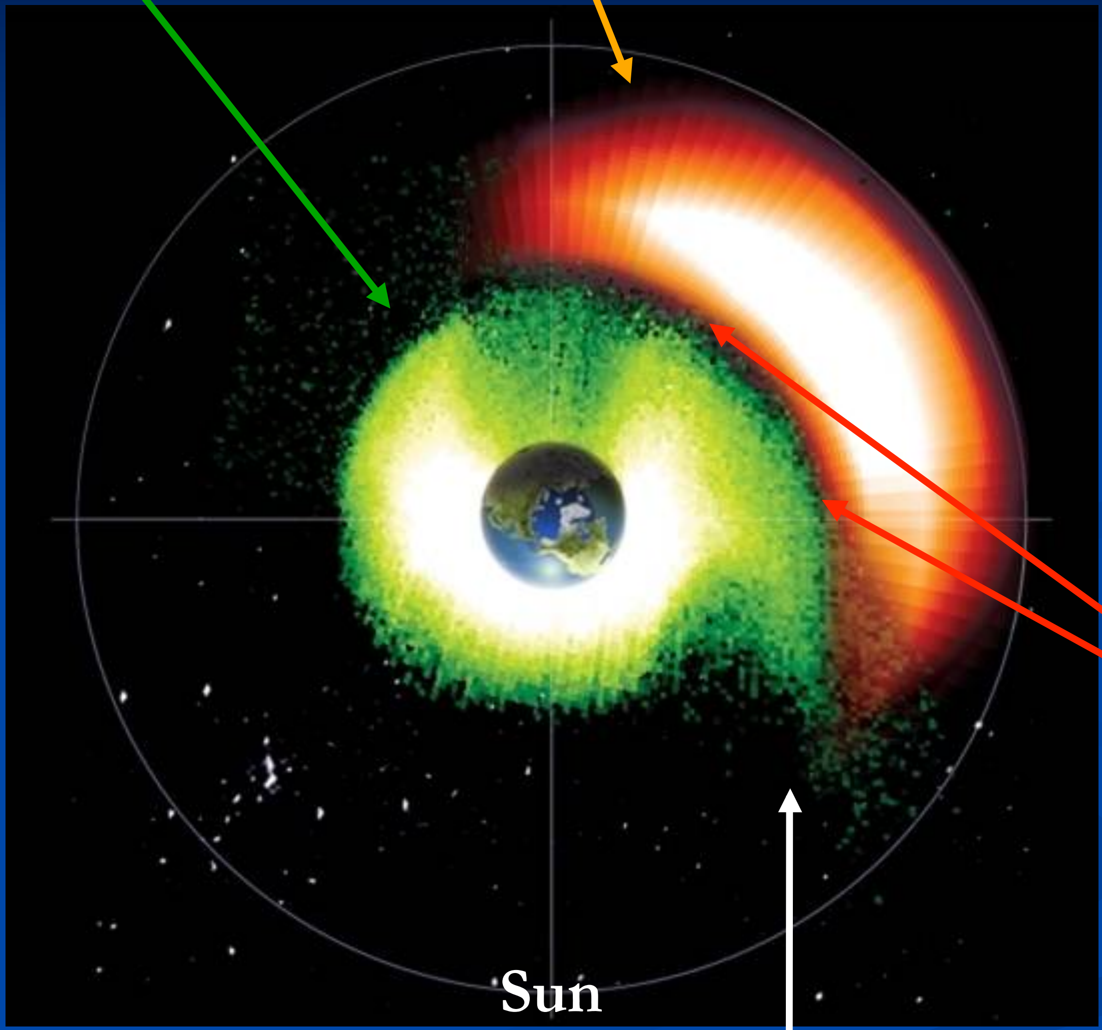


IMAGE Data of Plasmasphere





Plasmasphere / Ring Current Interactions



April 17, 2002
NASA IMAGE

SAPS Channel

Plasmasphere Erosion Plume

(Merged image courtesy J. Goldstein)

Outline

ABC's of GPS

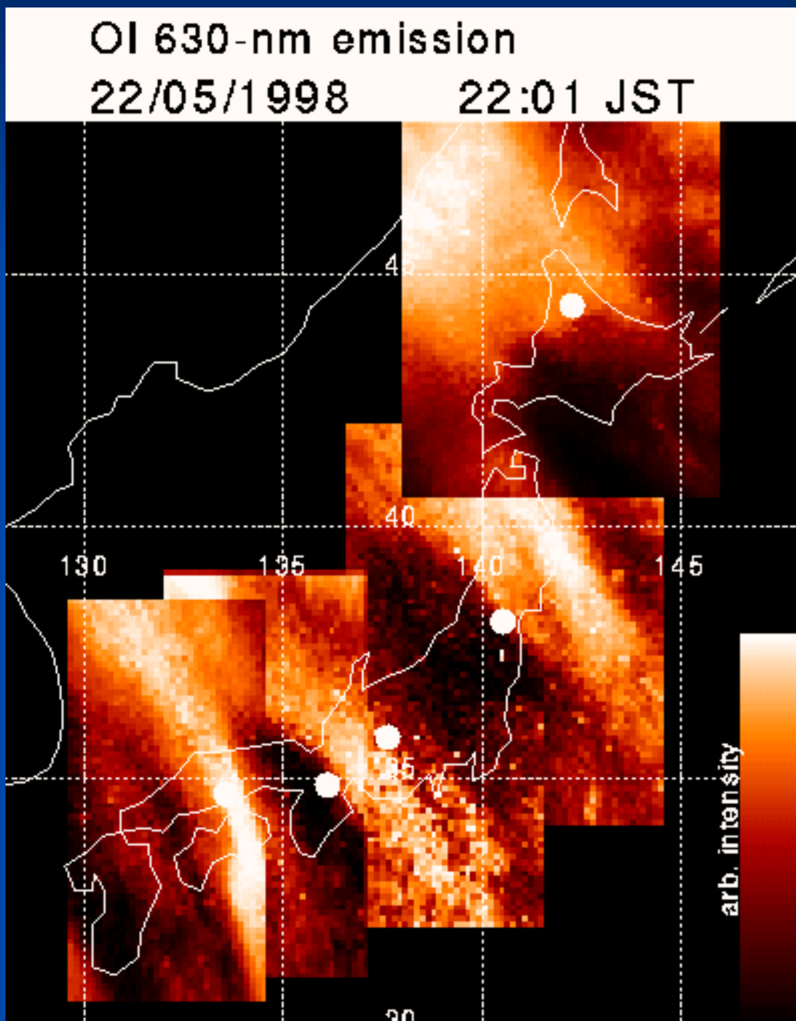
Some history of measuring the ionosphere with GPS

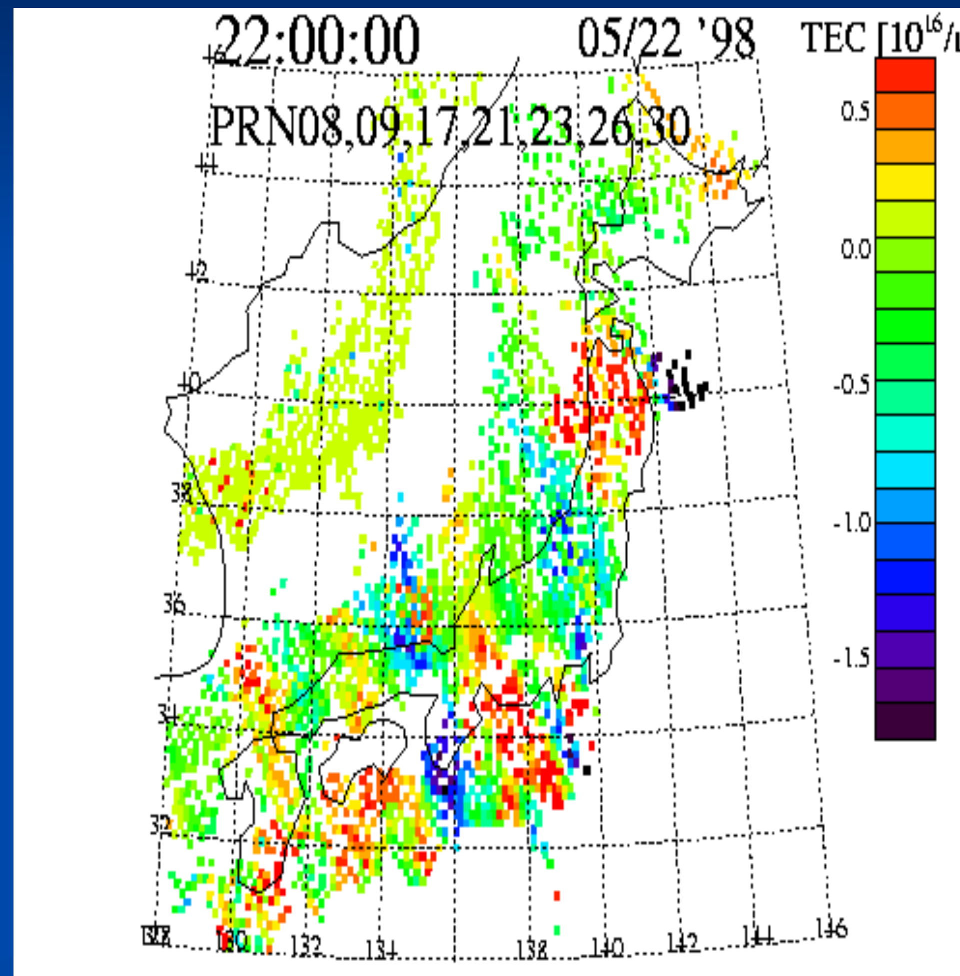
➡ IT Coupling – GPS

MI Coupling – GPS

What's on the horizon

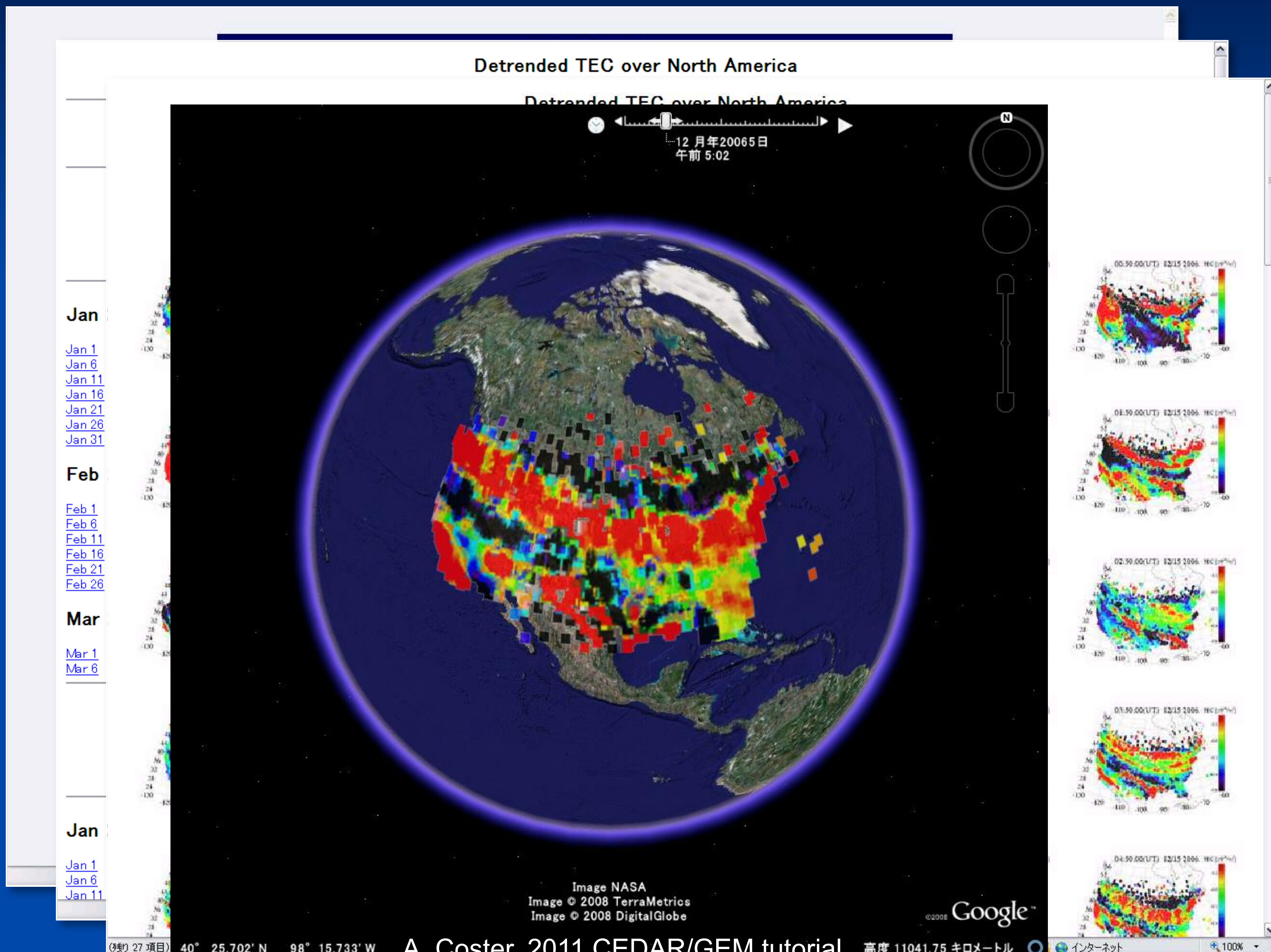
Nighttime MSTID Observations (TEC, Airglow) [*Saito et al*., 2001]





TEC data of American-wide GPS Network（TEC-DAWN)

http://www2.nict.go.jp/y/y223/member/tsugawa/TEC-DAWN/



The following movie is to show

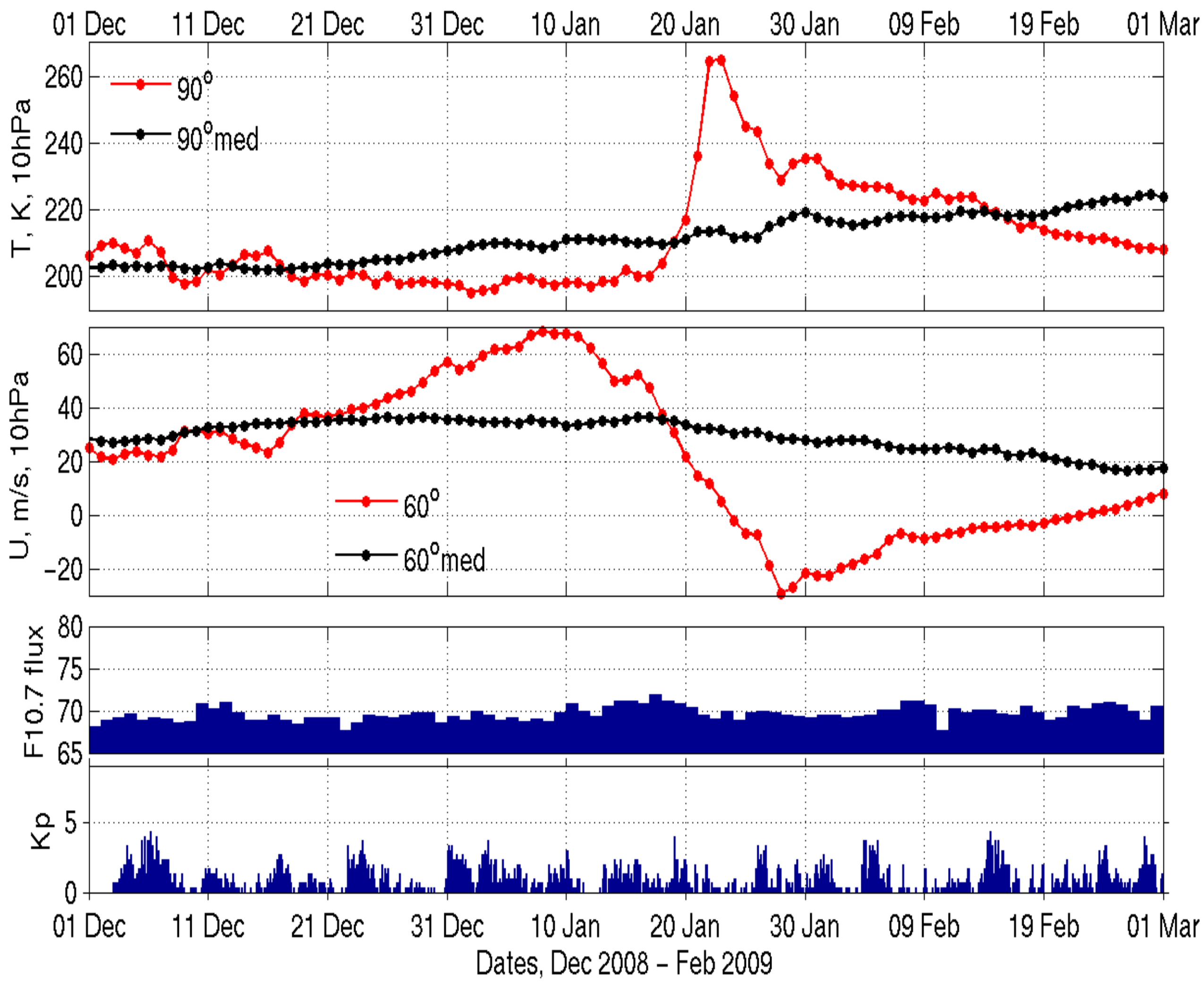
that people have been

concerned with the stratosphere for a long time …

Zombies in the Stratosphere

http://www.youtube.com/watch?v=6z7IoYeVAuc&feature=related

Sudden Stratospheric Warming and Solar Parameters [Jan 2009]



Stratospheric Temperature over the Arctic

Stratospheric Zonal wind at 60°N

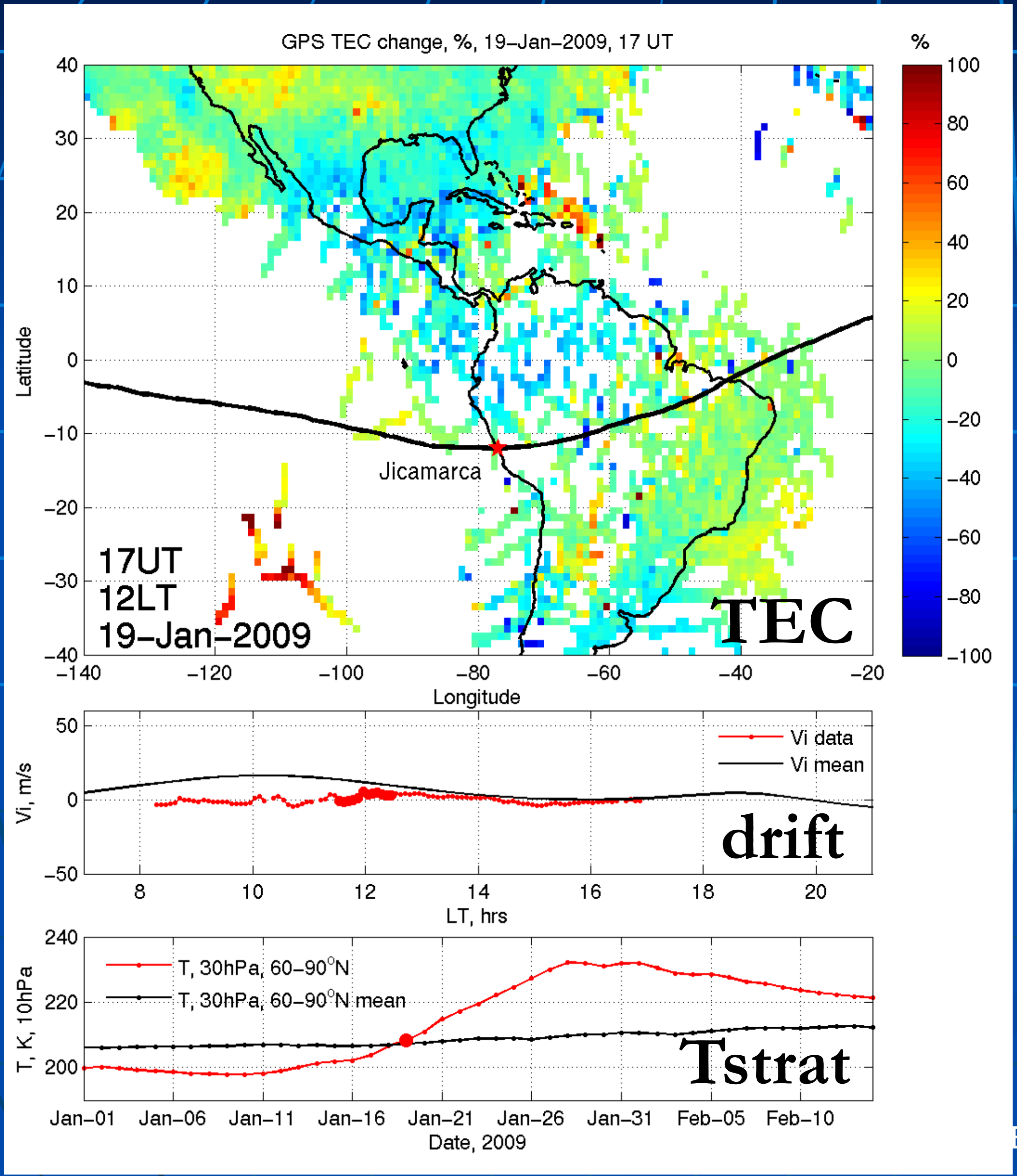
Solar activity

Minimum: F10.7< 80

Magnetic activity

Quiet: Kp < 3

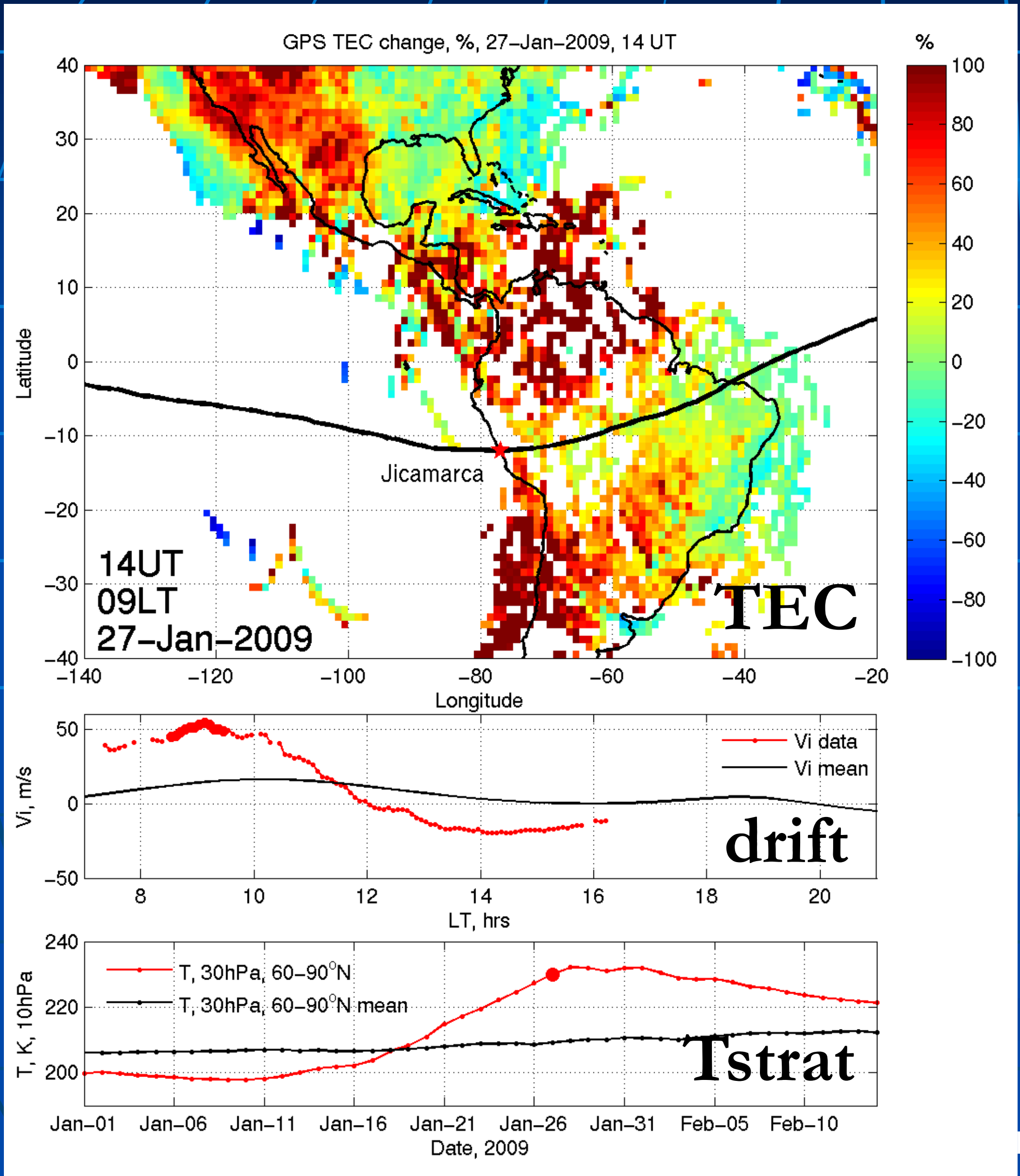
GPS TEC change – no warming



- GPS TEC (Total Electron Content) data show large-scale picture of ionospheric behavior
- Before the warming, TEC change is 10-20% from mean and vertical drift is small
- The mean is Jan 1-14, 2009

51

GPS TEC during warming: morning sector



- During stratwarming, TEC increases in excess of 50-100% in the morning
- Large upward drift at Jicamarca
- The magnitude of increase is similar to effects of severe geomagnetic storms

Outline

ABC's of GPS

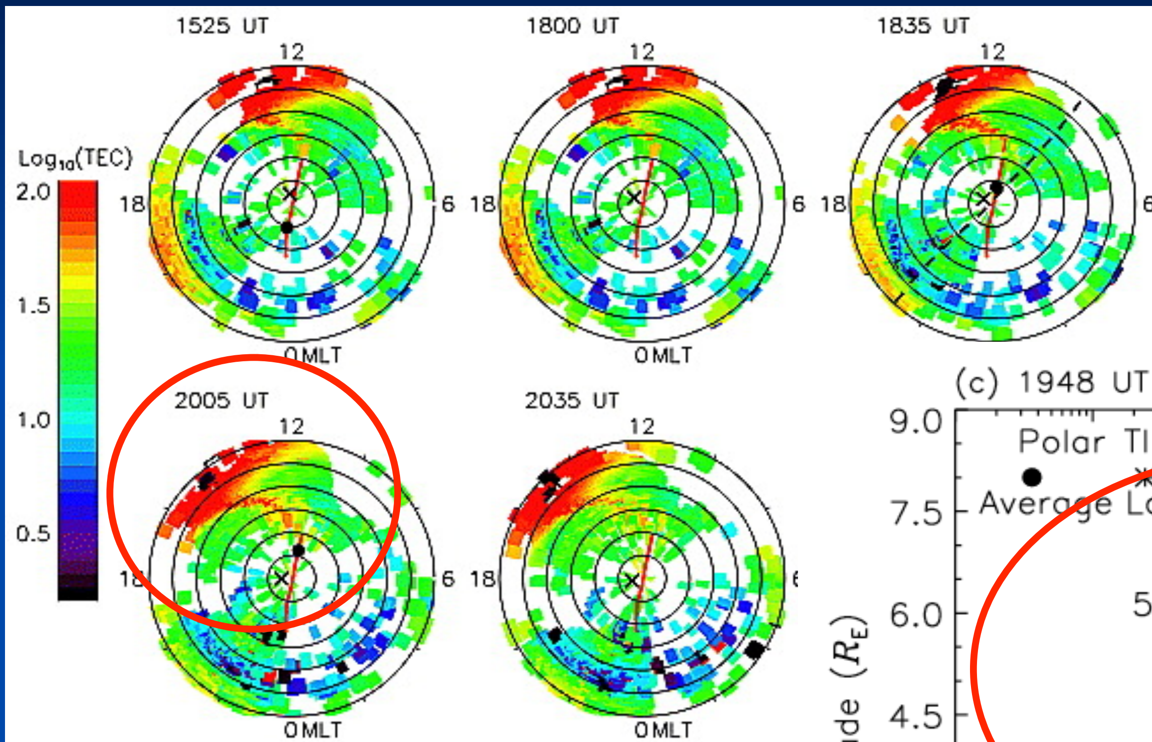
Some history of measuring the ionosphere with GPS

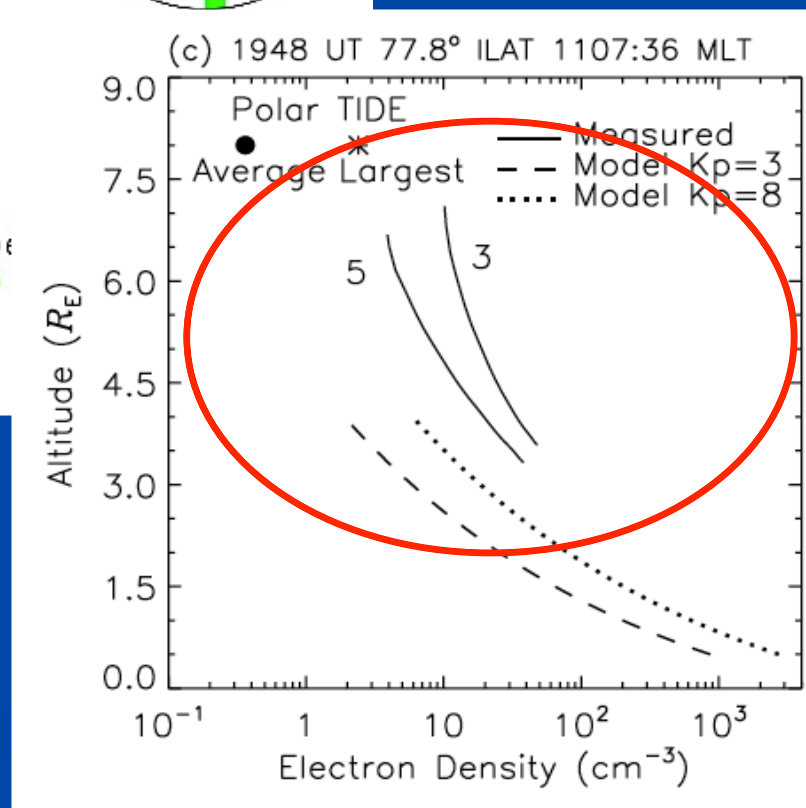
IT Coupling – GPS

➡ MI Coupling – GPS

What's on the horizon

J.-N. Tu, et al., JGR, 2007, Extreme polar cap density enhancements along magnetic field lines during an intense geomagnetic storm





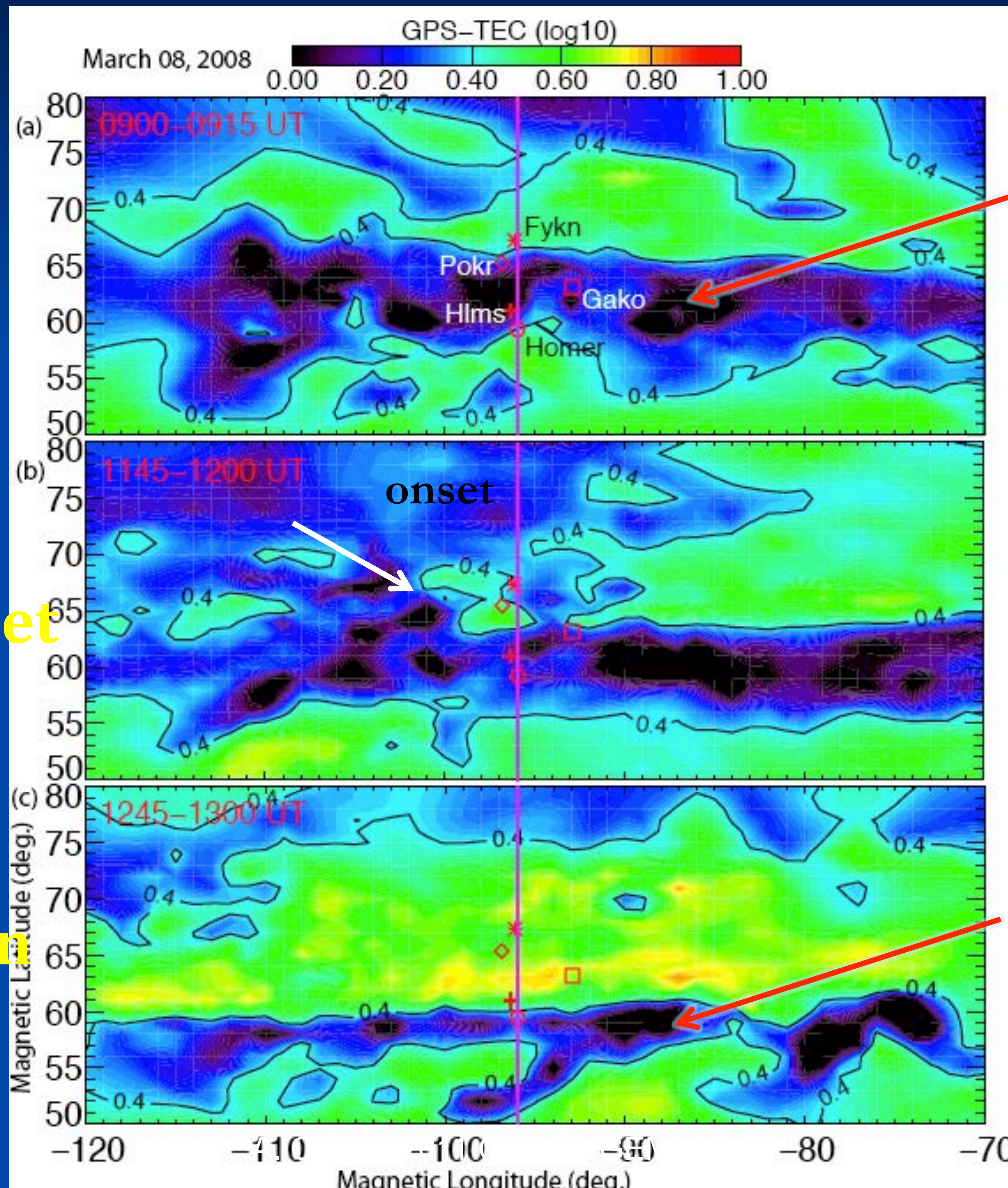
2D GPS VTEC Contour over Alaska: 2008/03/08 ~11:40 UT Event

Zou, S., et al., 2011, GRL

Before onset

Right after onset

Late expansion phase



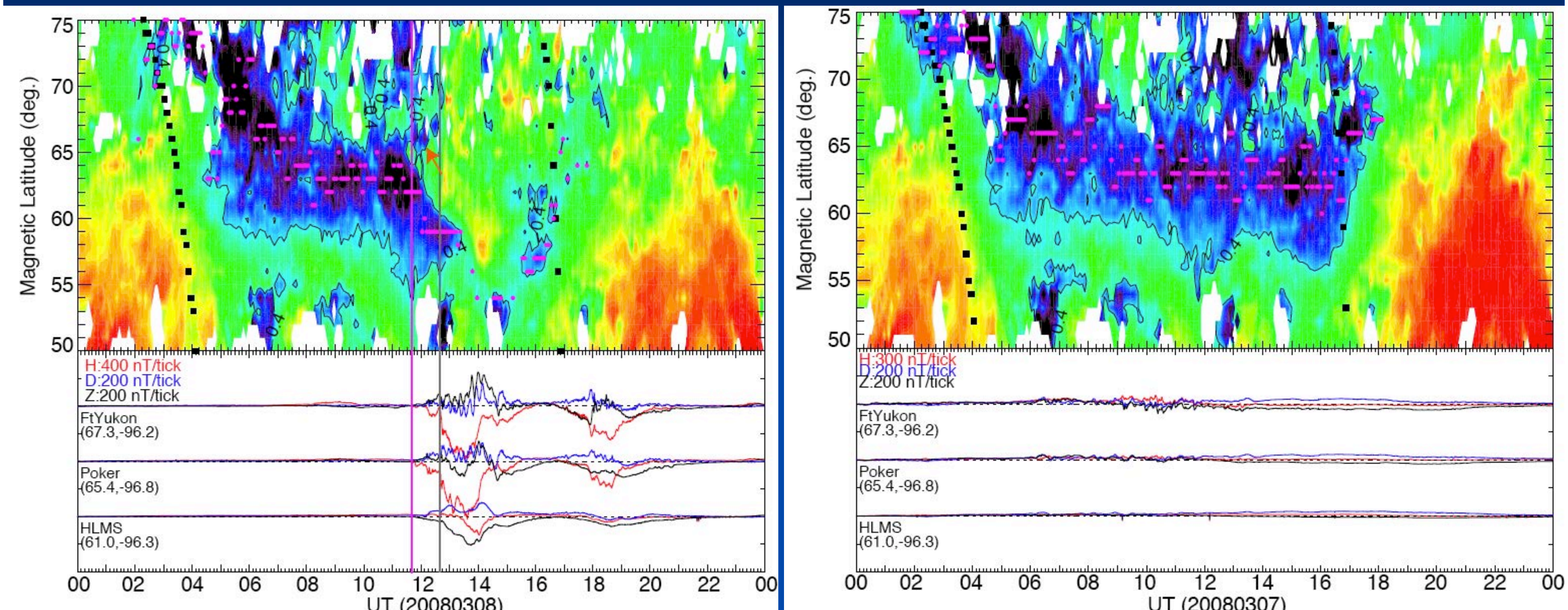
mid-latitude trough

Narrowing of mid-latitude trough

Time Series of GPS VTEC Over Central Alaska

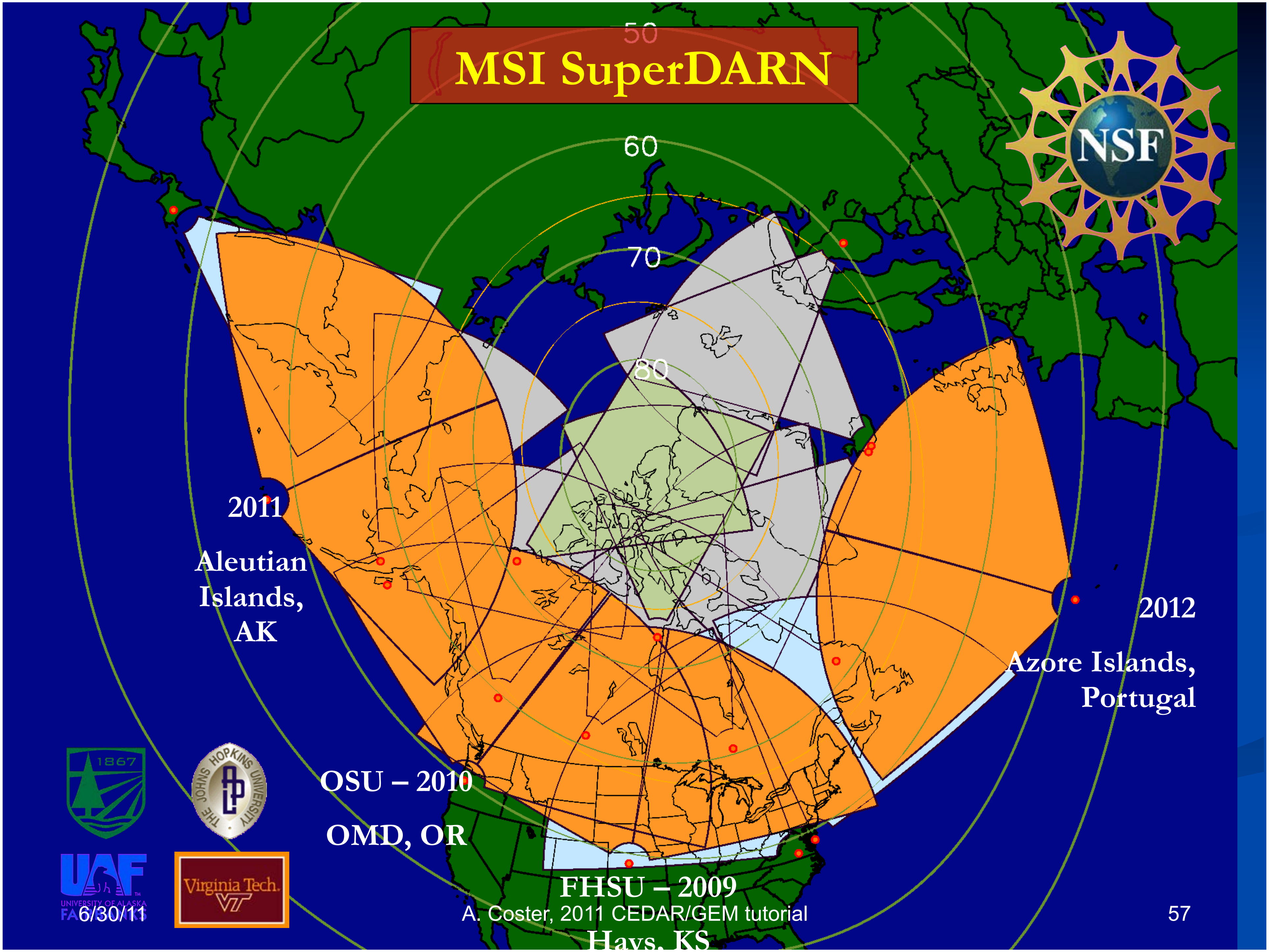
Zou, S., et al., 2011, GPS TEC observations of dynamics of the mid-latitude trough during substorms, GRL

Disturbed day | Quiet day

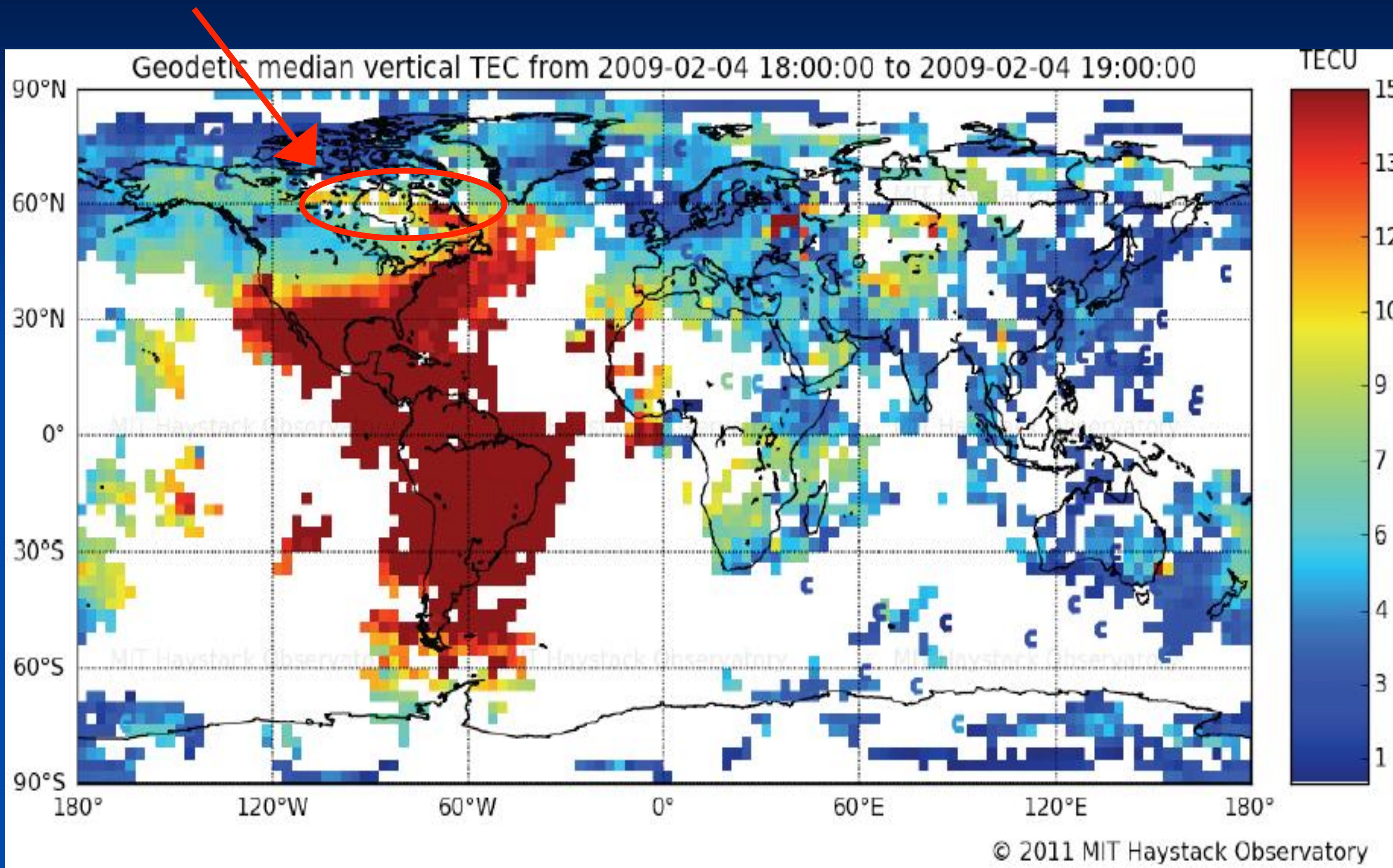


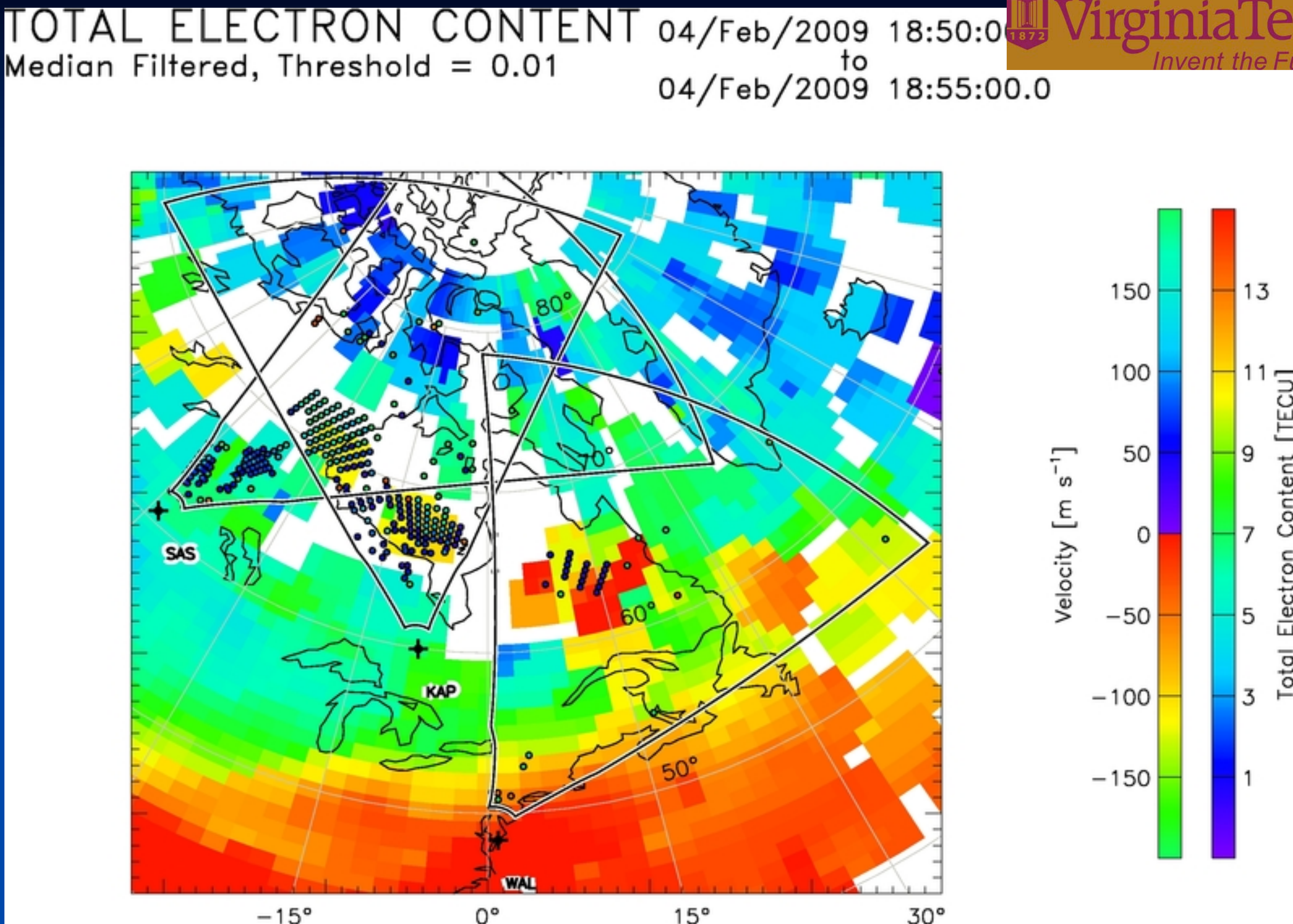
- ❖ Dramatic differences in GPS TEC distribution due to substorm activity;
- ❖ Filling of the mid-latitude trough during the expansion phase and reappearance during the recovery phase;
- ❖ Remotely sense the dynamics of the inner edge of the plasma sheet.

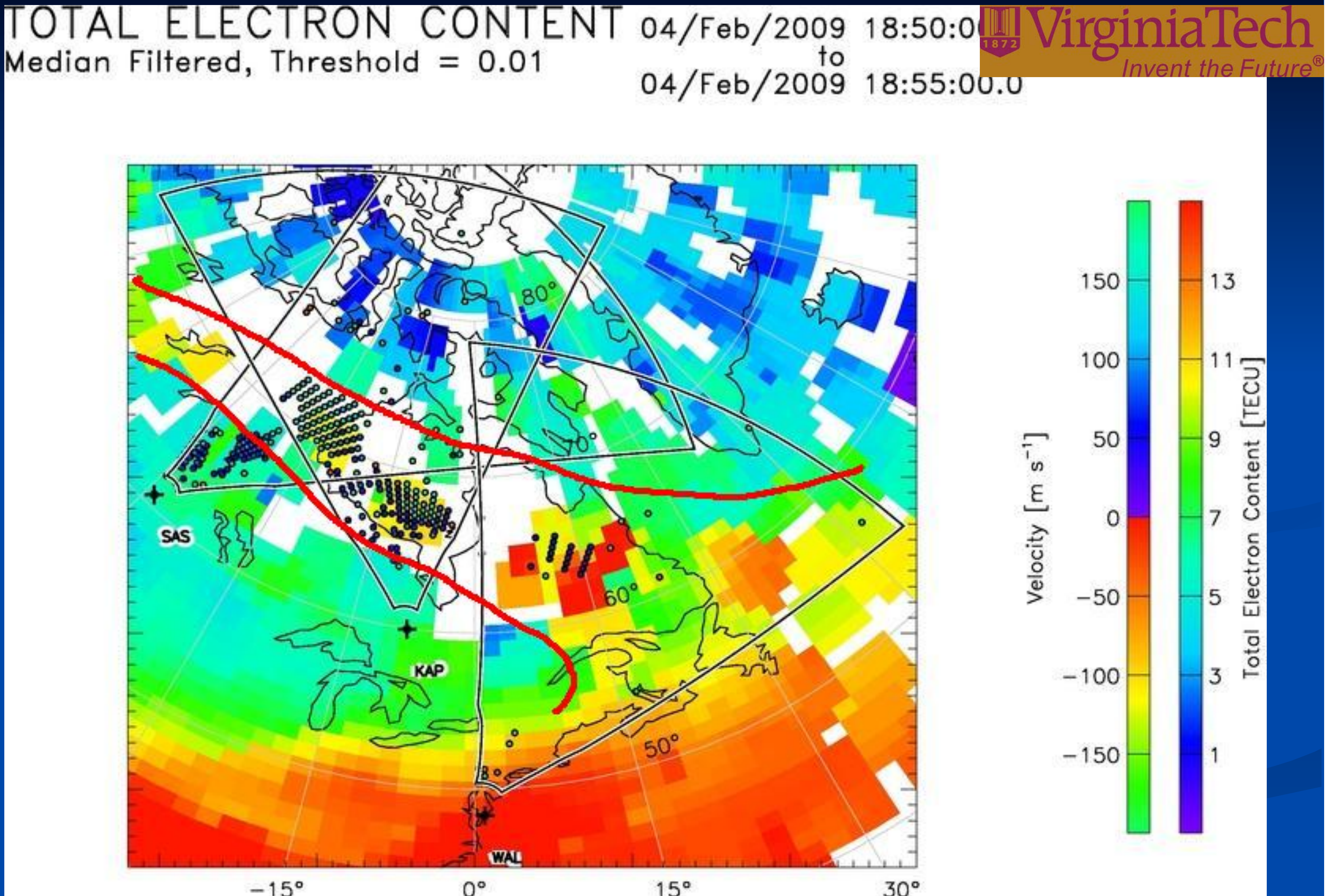
MSI SuperDARN



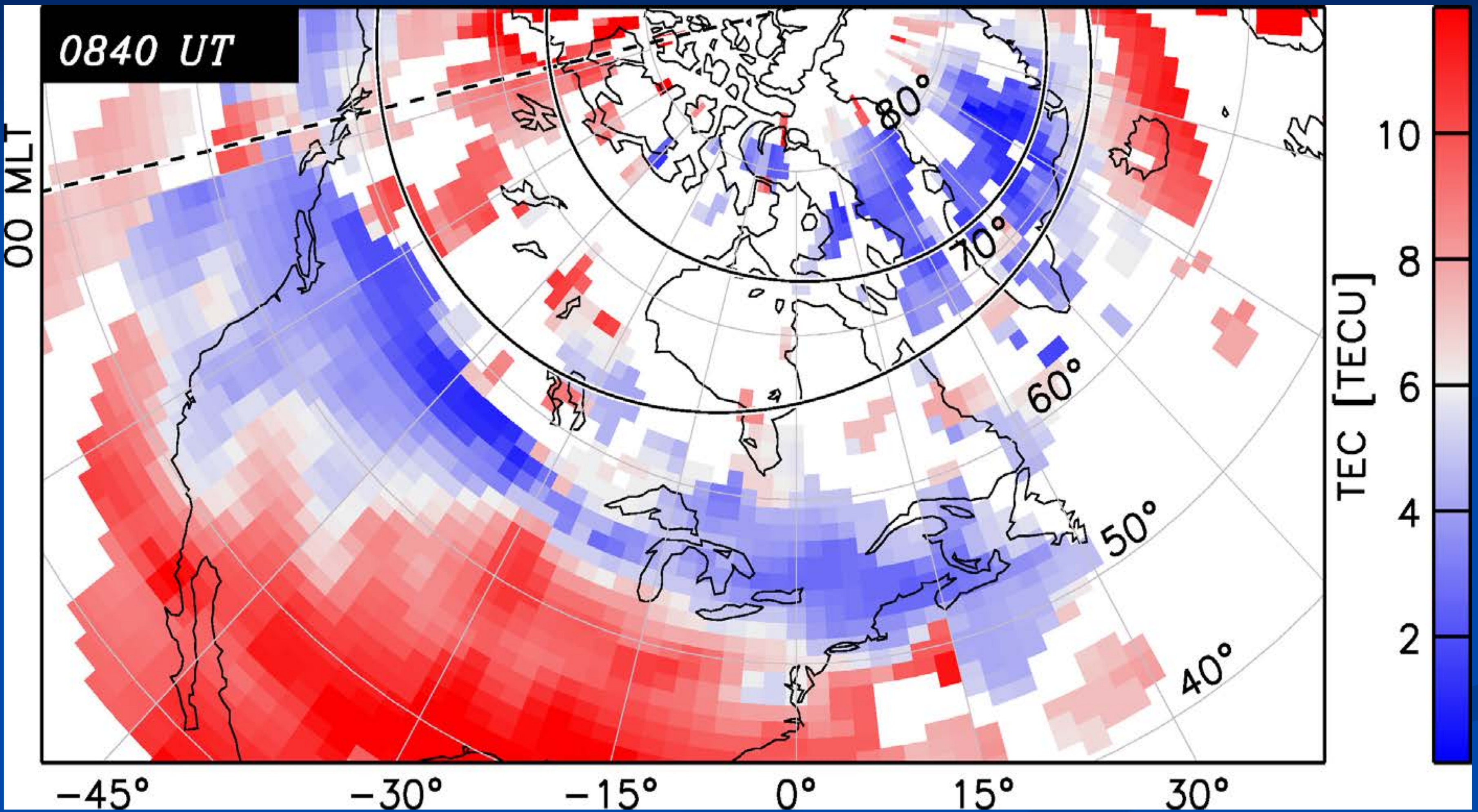
A storm enhanced density (SED)

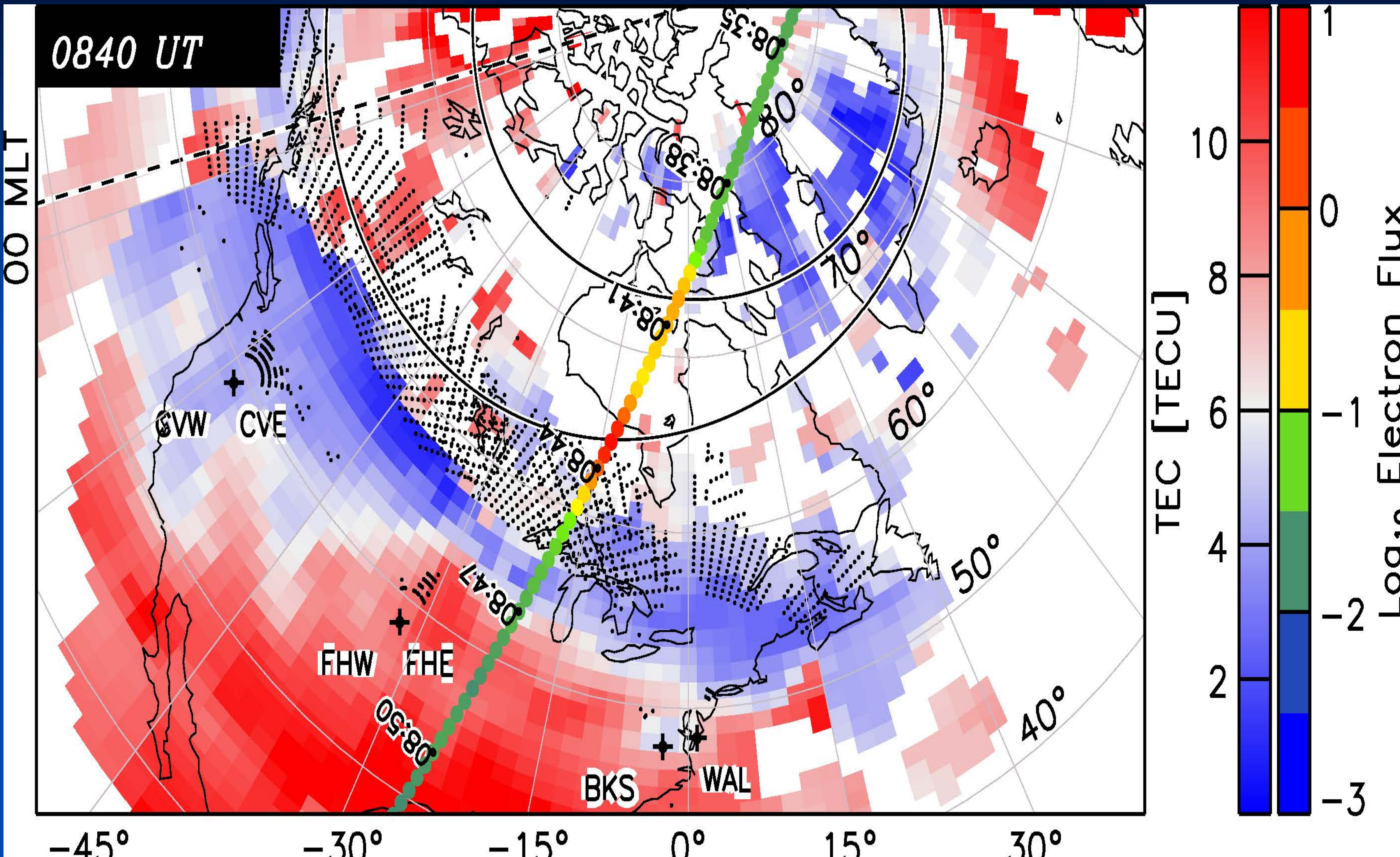



TOTAL ELECTRON CONTENT
Median Filtered, Threshold = 0.01
04/Feb/2009 18:50:00
to
04/Feb/2009 18:55:00.0
80°
70°
60°
50°
SAS
KAP
WAL
−15°
0°
15°
30°
Velocity [m s⁻¹]
150
100
50
0
−50
−100
−150
Total Electron Content [TECU]
13
11
9
7
5
3
1


TOTAL ELECTRON CONTENT
Median Filtered, Threshold = 0.01
04/Feb/2009 18:50:00
to
04/Feb/2009 18:55:00.0
VirginiaTech
Invent the Future®
80°
70°
60°
50°
SAS
KAP
WAL
−15°
0°
15°
30°
Velocity [m s⁻¹]
150
100
50
0
−50
−100
−150
Total Electron Content [TECU]
13
11
9
7
5
3
1

SAPS Event




0840 UT
00 MLT
08:35
08:38
08:41
08:44
08:47
08:50
80°
70°
60°
50°
40°
CVW
CVE
FHW
FHE
BKS
WAL
-45°
-30°
-15°
0°
15°
30°
TEC [TECU]
10
8
6
4
2
Log10 Electron Flux
1
0
-1
-2
-3

Ionospheric Tomography with GPS

Yizengaw, et al., 2006b

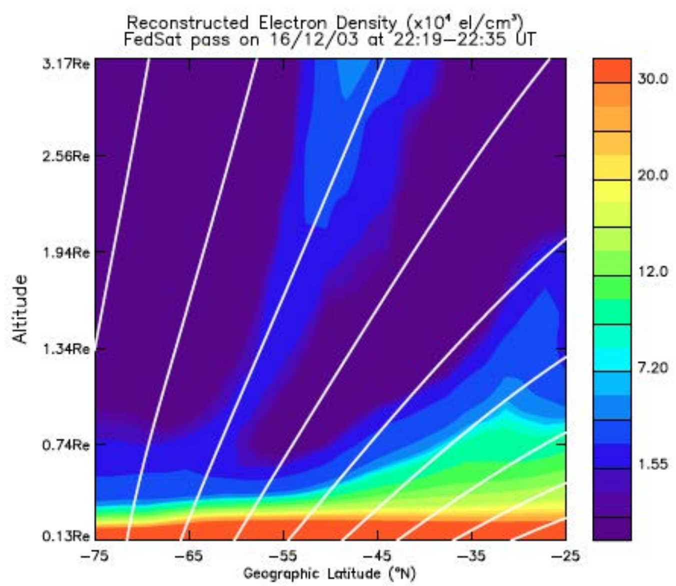
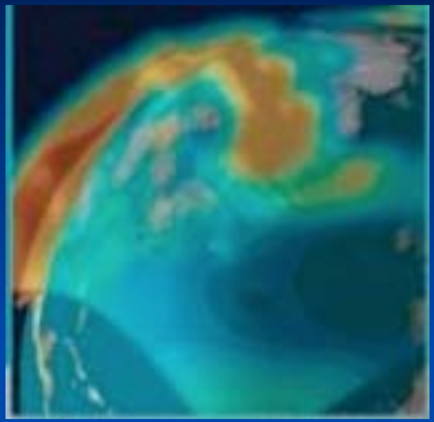
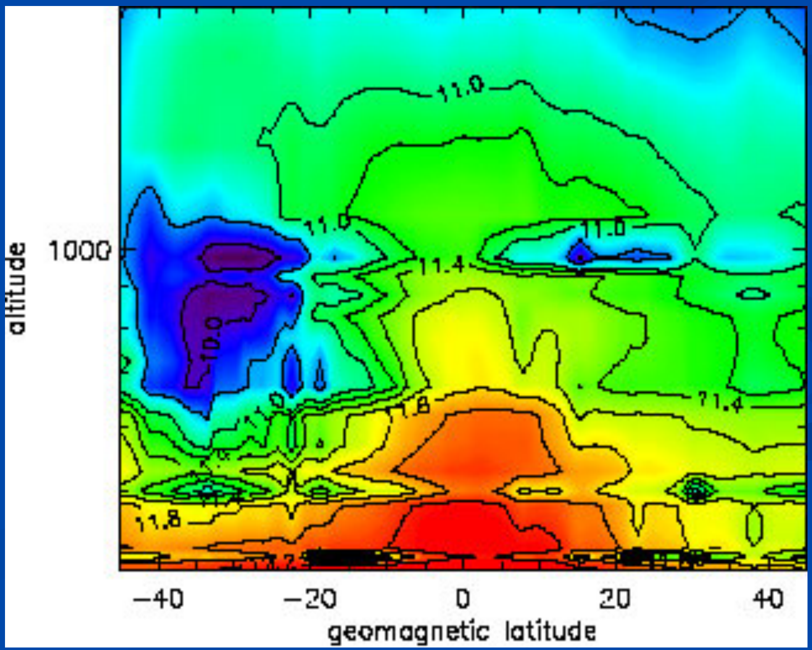


Figure 5. *Tomographically reconstructed density distribution using data recorded by GPS receiver on FedSat. The curved white lines depict the magnetic field lines obtained from Tsyganenko 01-model (after Yizengaw et al., 2006b).*

courtesy of C. Mitchell



Courtesy of G. Bust



Outline

ABC's of GPS

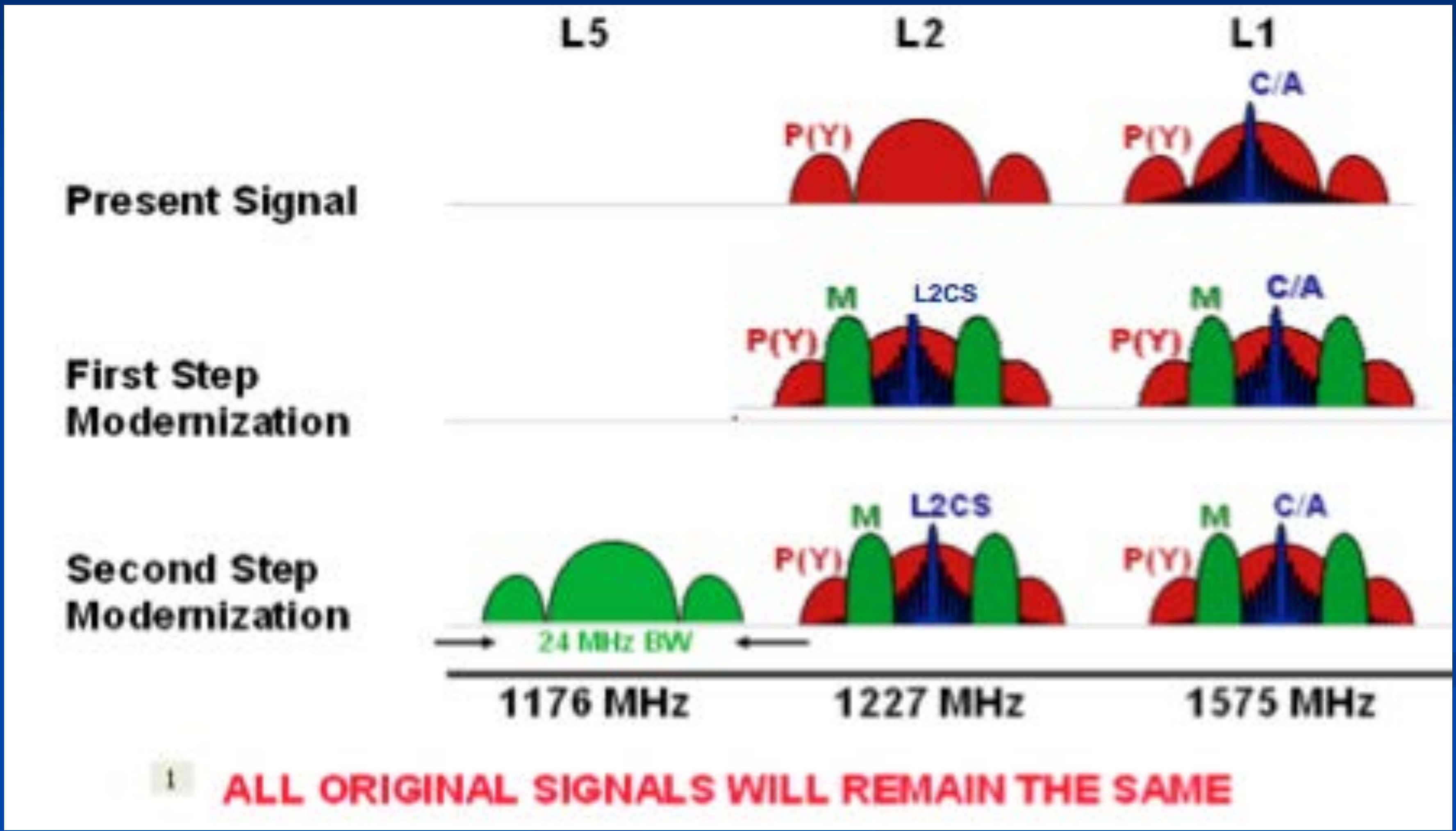
Some history of measuring the ionosphere with GPS

IT Coupling – GPS

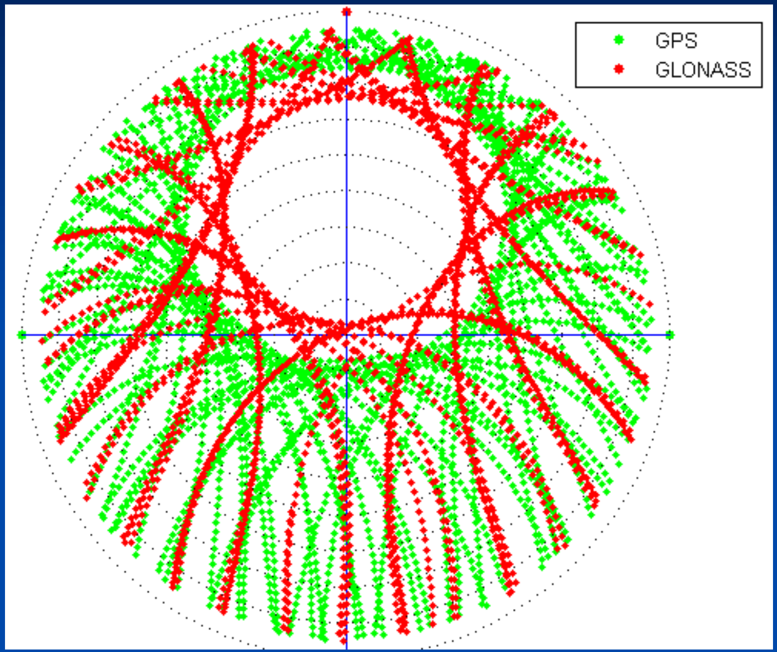
MI Coupling – GPS

What's on the horizon

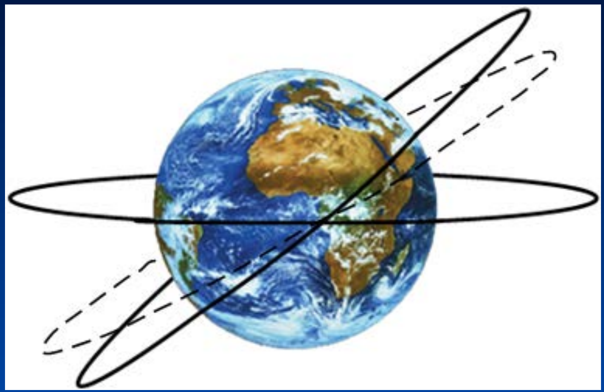
GPS Modernization



24-hour satellite path for GPS (Green) and GLONASS (Red)



GLONASS orbit plane inclination: 65°

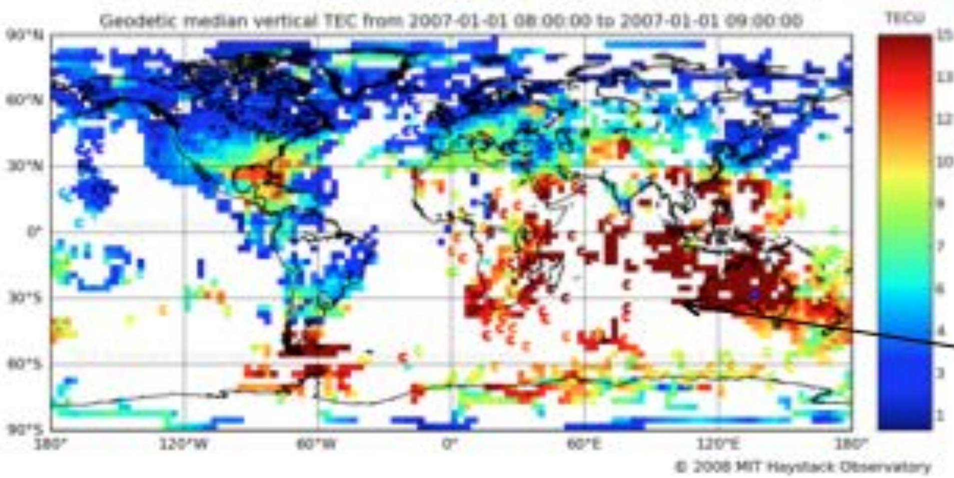


COMPASS

GALILEO

Improved Low-Cost, Low-Power GPS Measurements at Sea

Total Electron Content derived from GPS Ground and Space-Based (COSMIC) systems



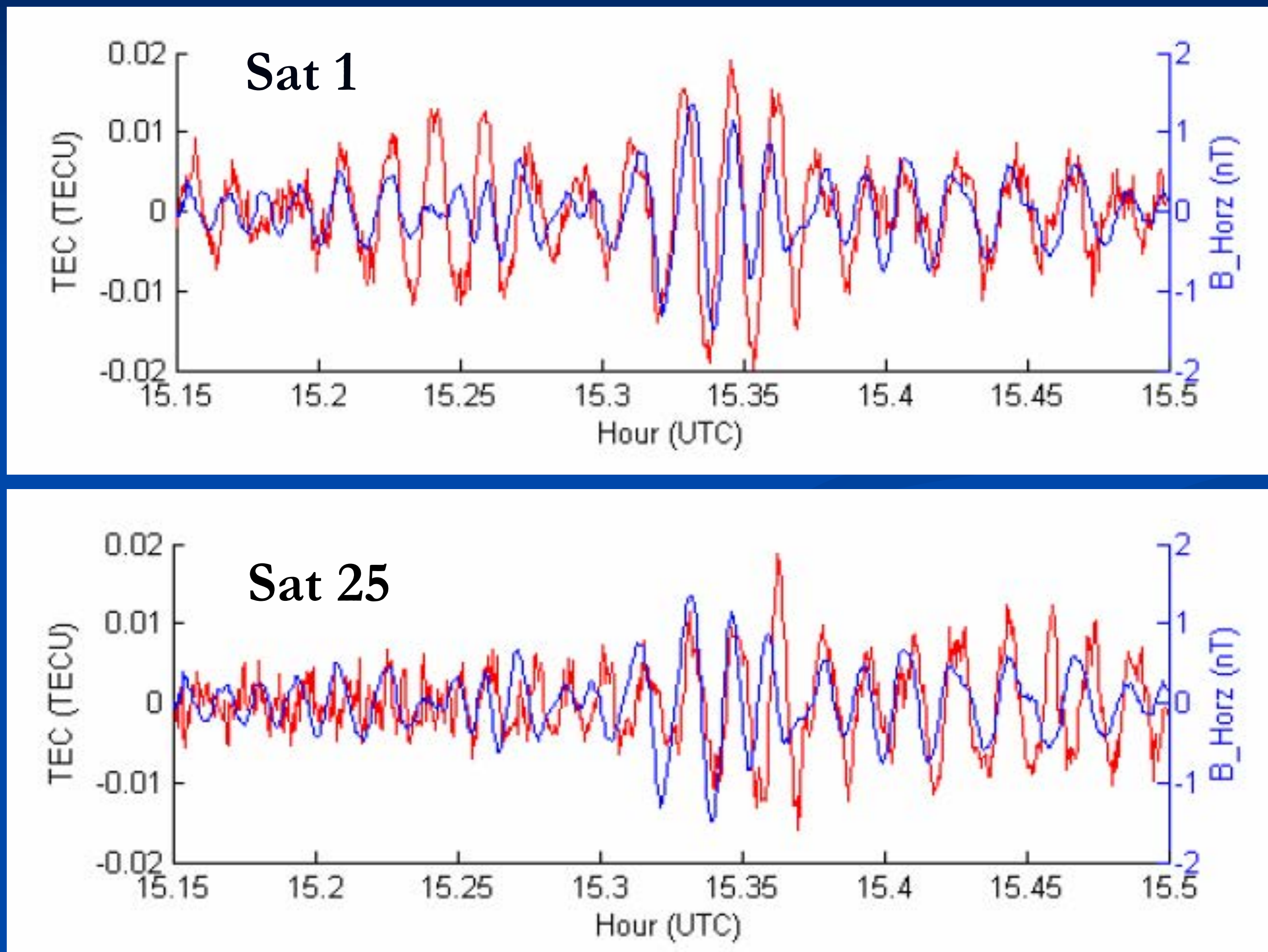
- **High Precision GPS Measurements at Sea are lacking due to:**
  1. **Cost**
  2. **Power**
  3. **Lack of civilian signal on second frequency**

White areas indicate no data

Why Now ?

- **Modernized GPS offers new civilian signals on two new frequencies**
- **New software receivers use less power and substantially reduce cost (factor of ~5)**

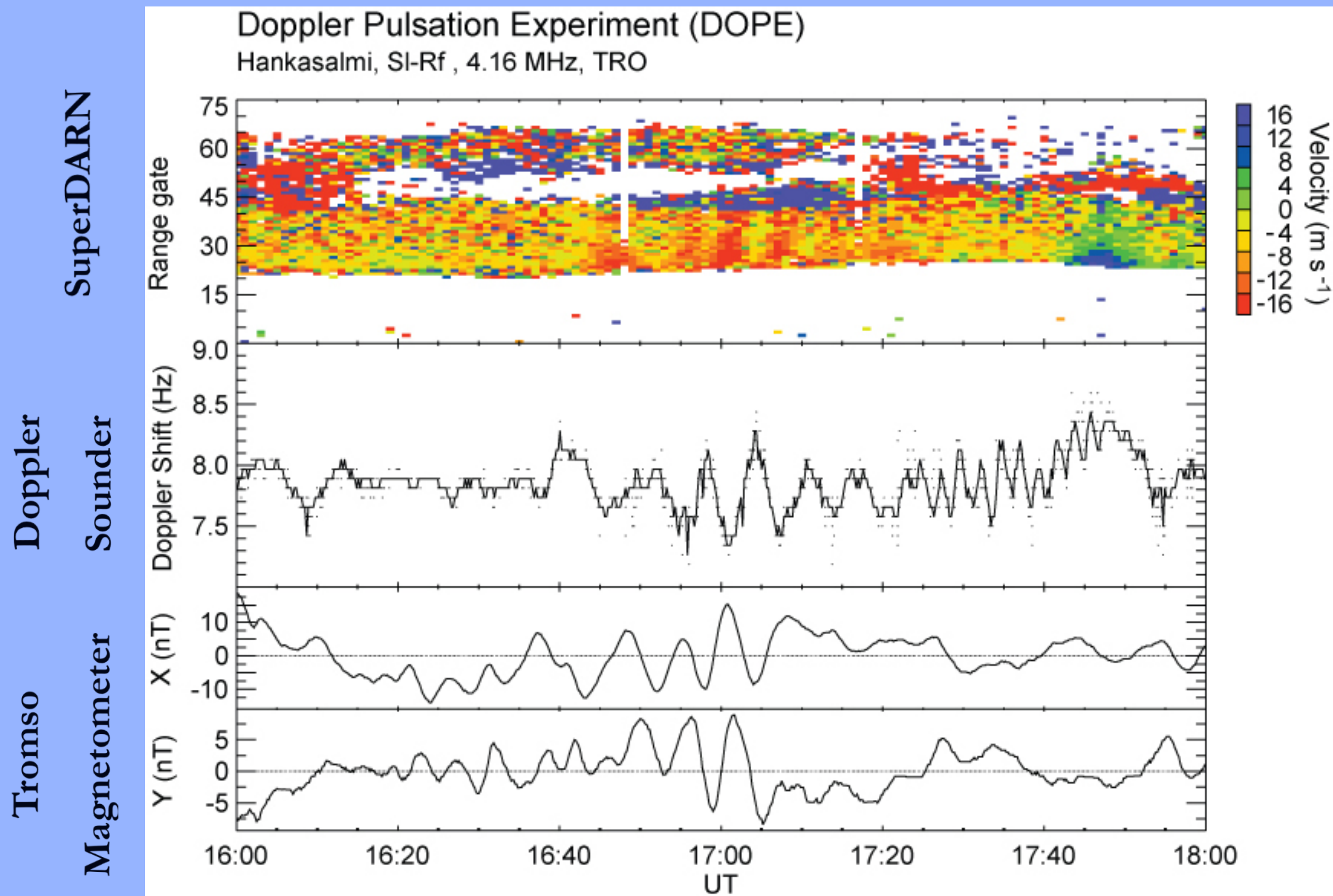
Correlation of magnetometer measurements with GPS TEC



Skone, 2006

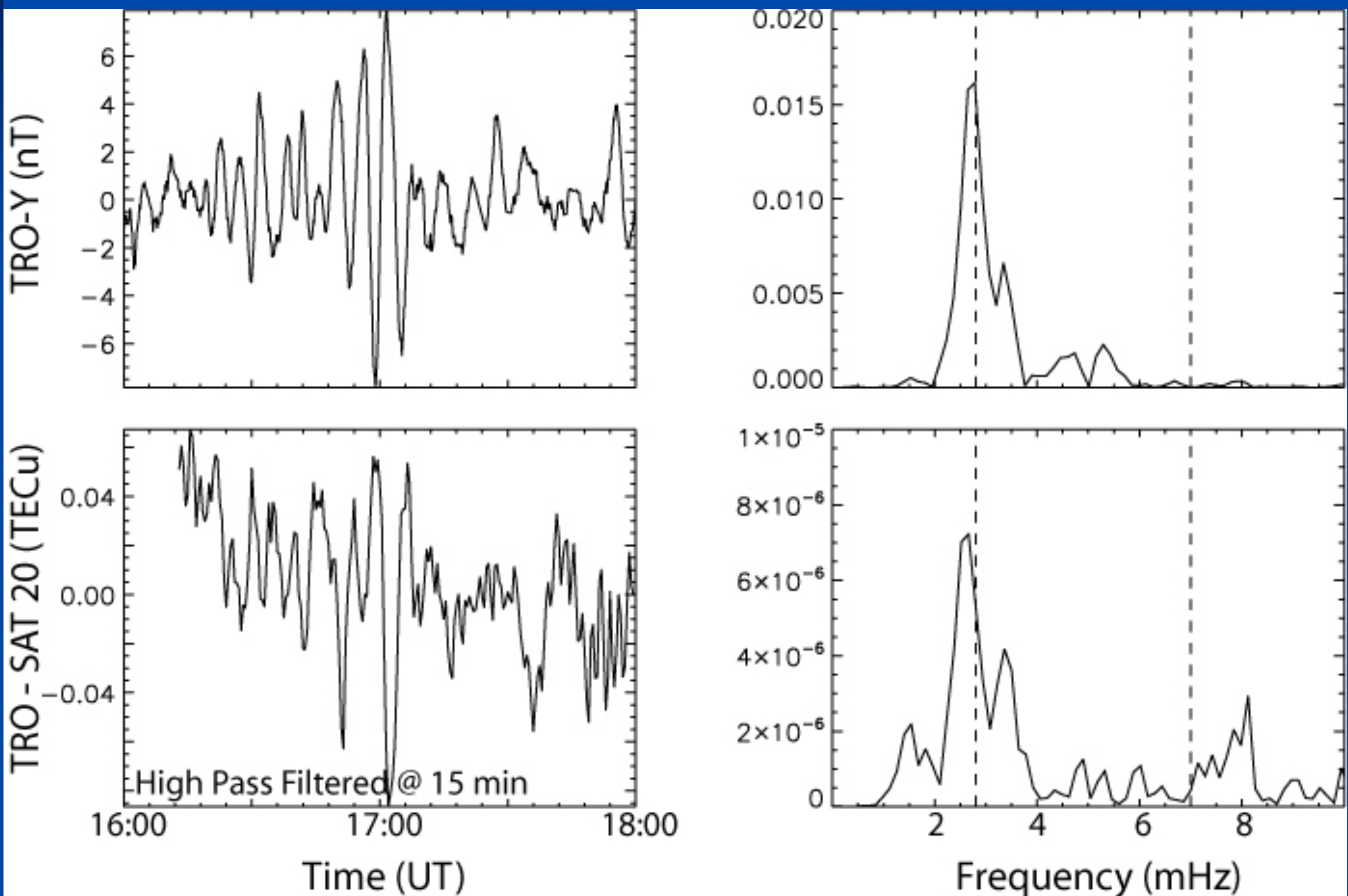
Example of small-scale pulsations not observed on the ground

courtesy of D. Murr



Waters et al., 2007

Comparison of Tromso TEC from SAT 20 and ground magnetometer



SUMMARY

In this last decade, global GPS TEC maps have provided a paradigm shift in the way we study the ionosphere/plasmasphere/magnetosphere.

GPS has played a key role in system science studies of the atmosphere.

I believe that we are at a dawn of a new age with the combination of GNSS observations and other data sets. There are a lot of new discoveries buried in the data.