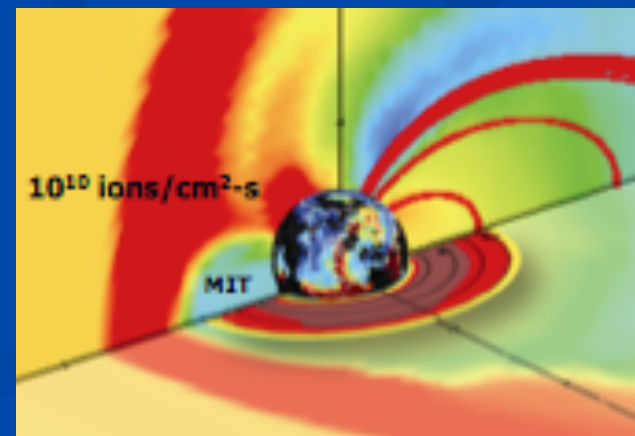




A Student Tutorial : Using GPS to Study Magnetospheric- Ionospheric Coupling

Anthea Coster
MIT Haystack Observatory



Outline



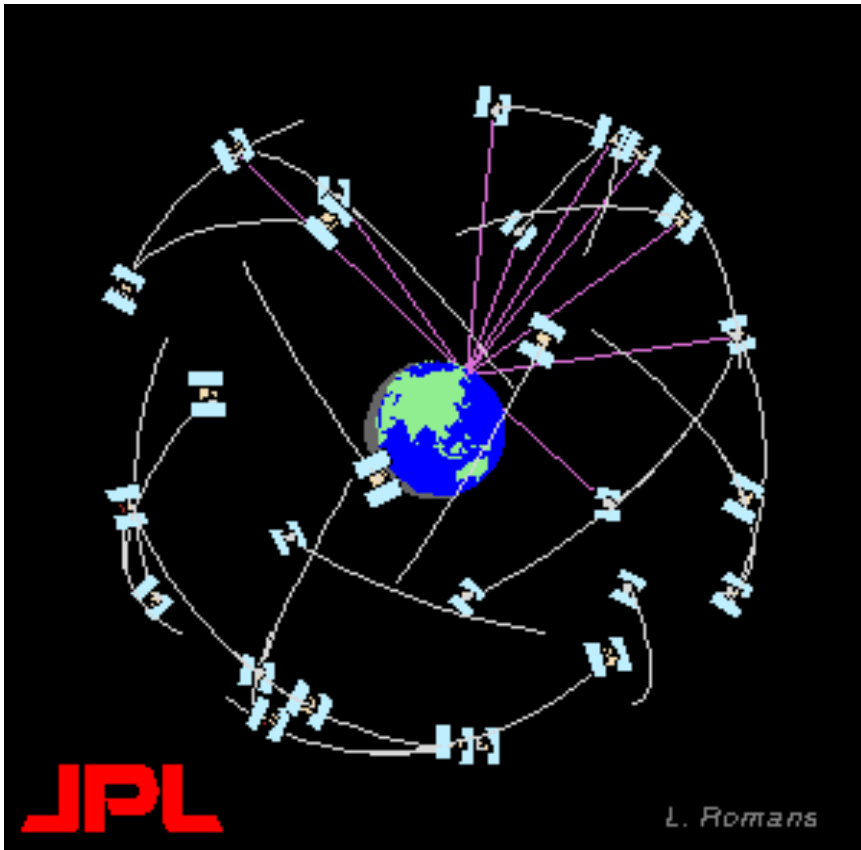
ABC's of GPS

History (some) of measuring the ionosphere with GPS

IT Coupling – GPS

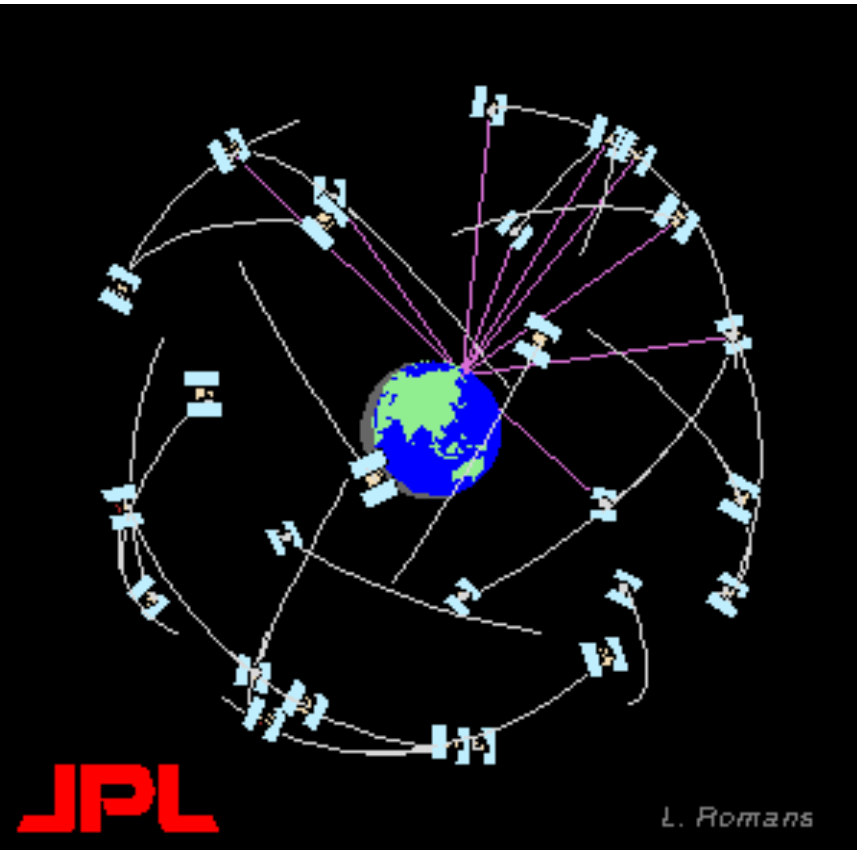
MI Coupling – GPS

What's on the horizon



GPS Background

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

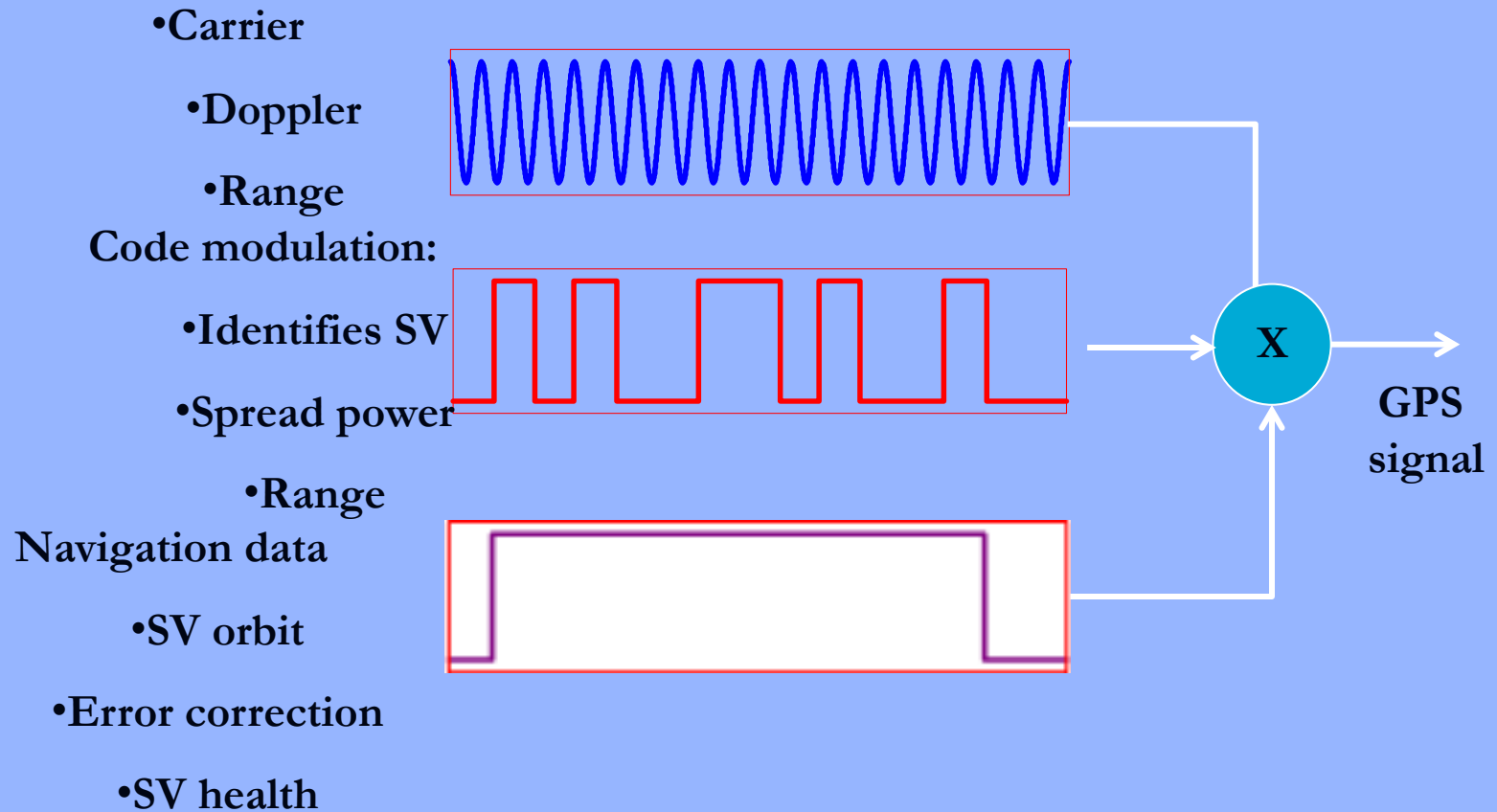


GPS Background

Each GPS spacecraft

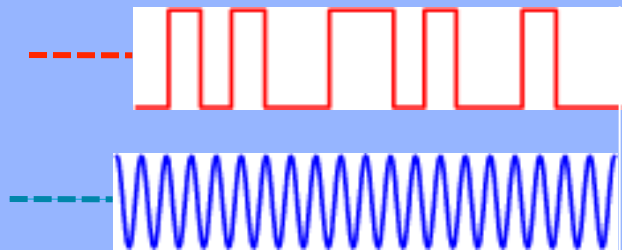
- **Carries highly accurate clock**
- **Transmits its clock and position**
- **Signals are transmitted on 2 (or 3) frequencies**

GPS Satellite Signal Structure



Range Measurements

Transmitted at SV:



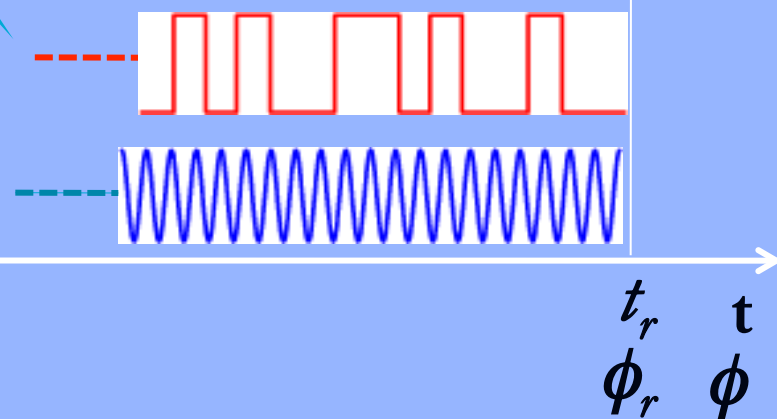
Pseudorange:

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

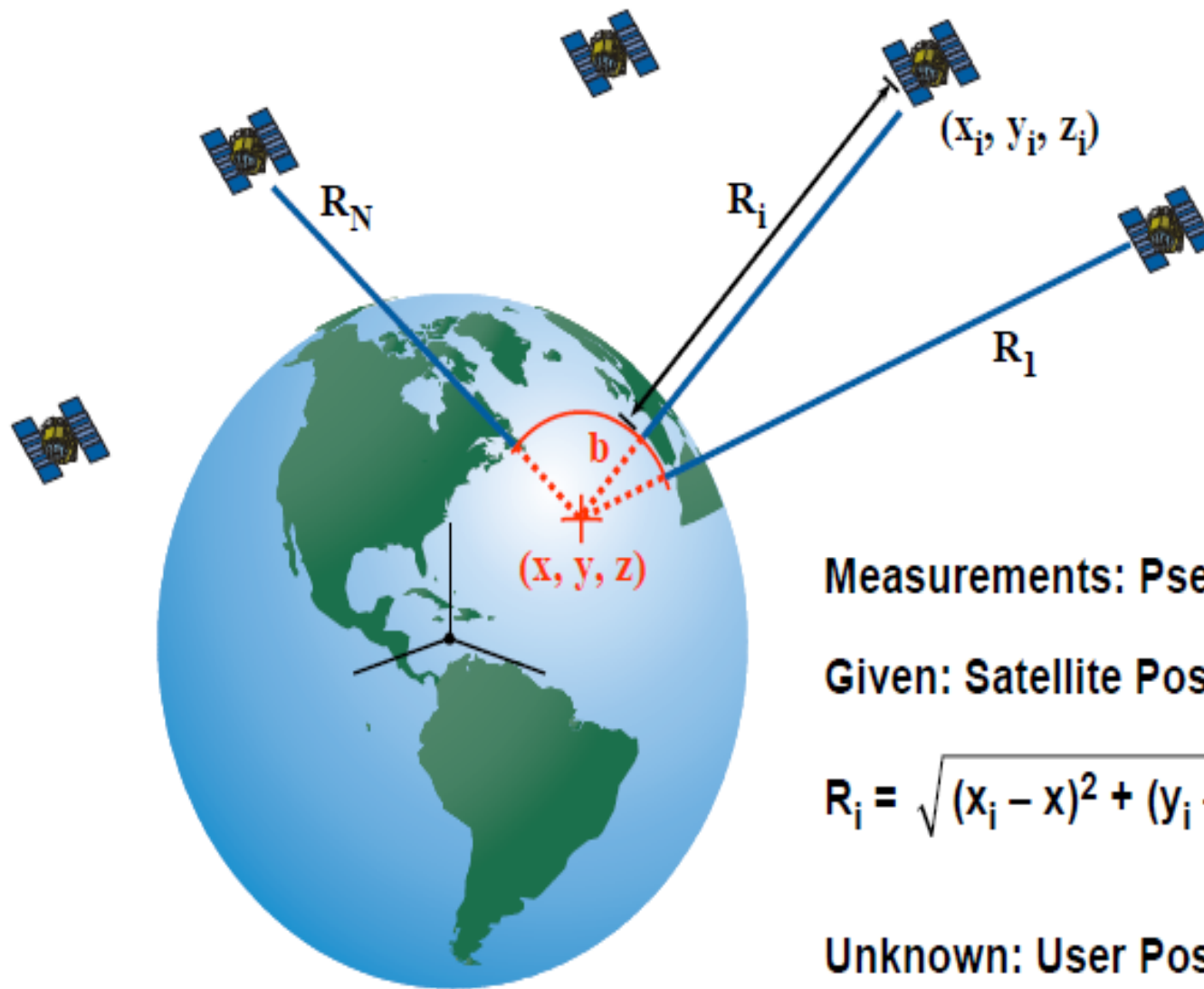
Carrier phase:

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

Received at RX:



GPS Positioning



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

Measurements: Pseudoranges $\{R_i\}$

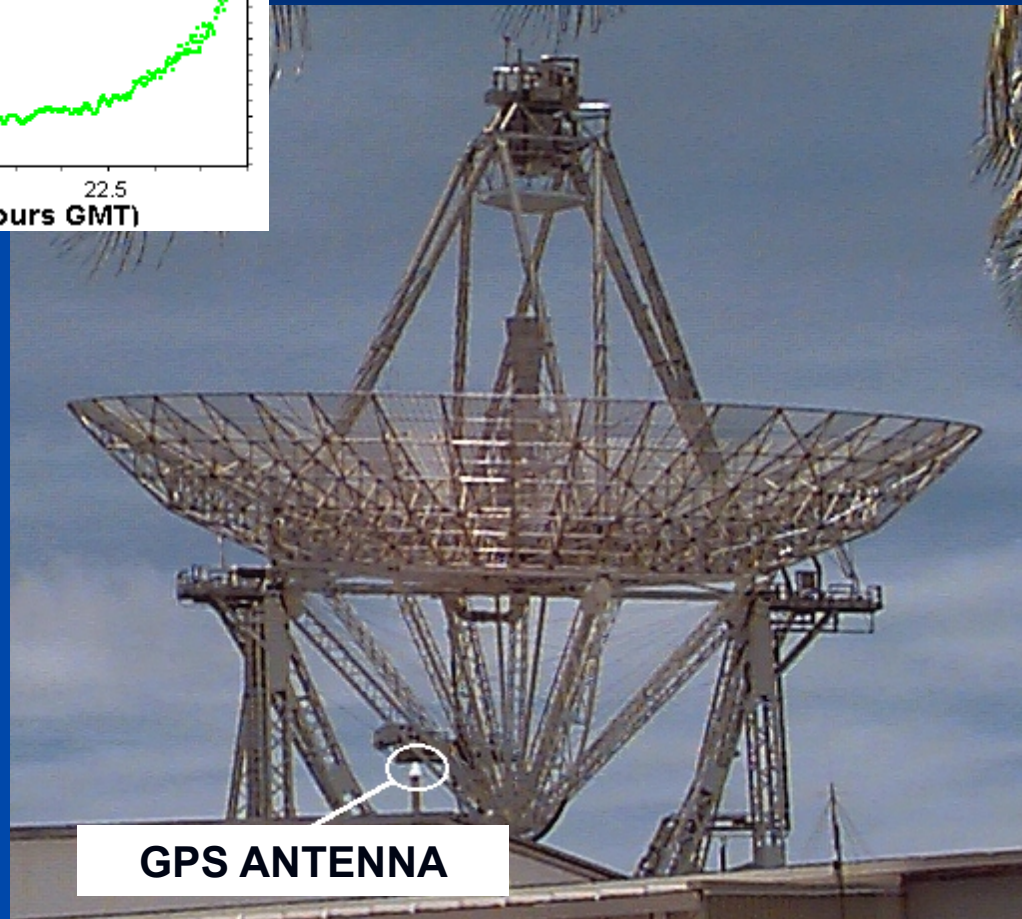
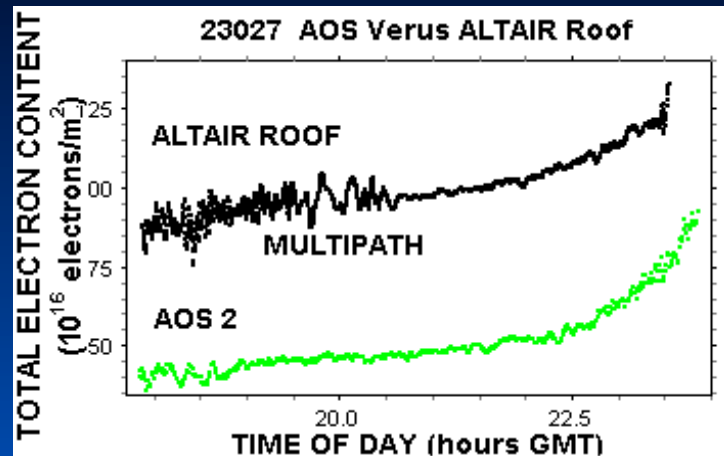
Given: Satellite Positions $\{(x_i, y_i, z_i)\}$

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

Unknown: User Position (x, y, z)

Receiver Clock Bias b

GPS Signal Multipath



Atmospheric Propagation

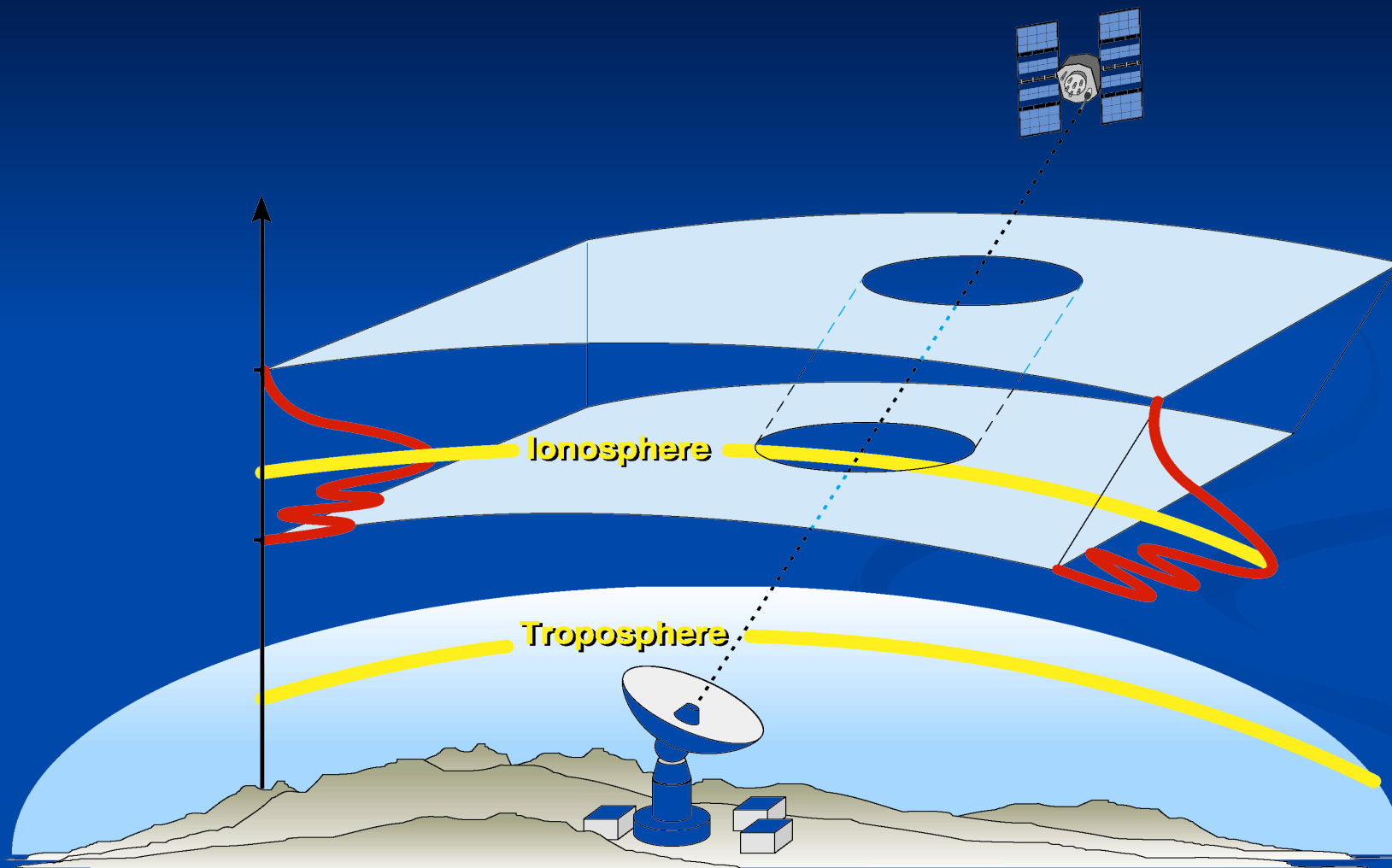
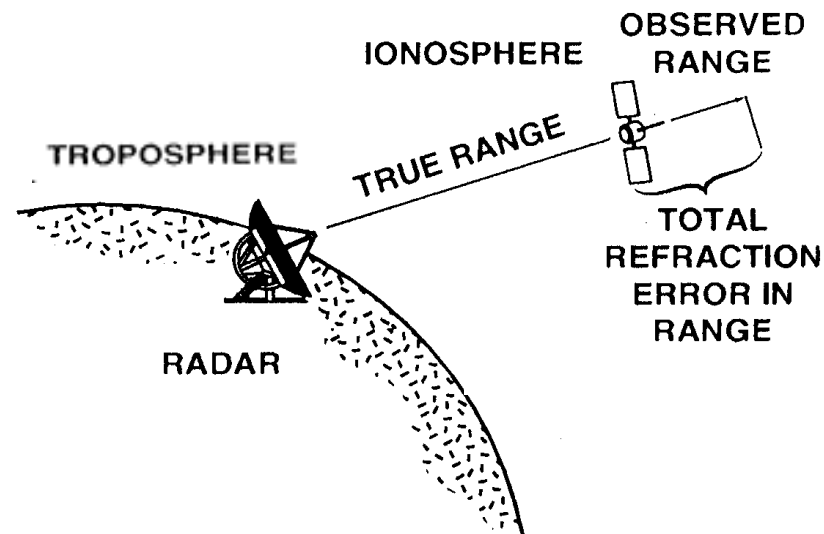
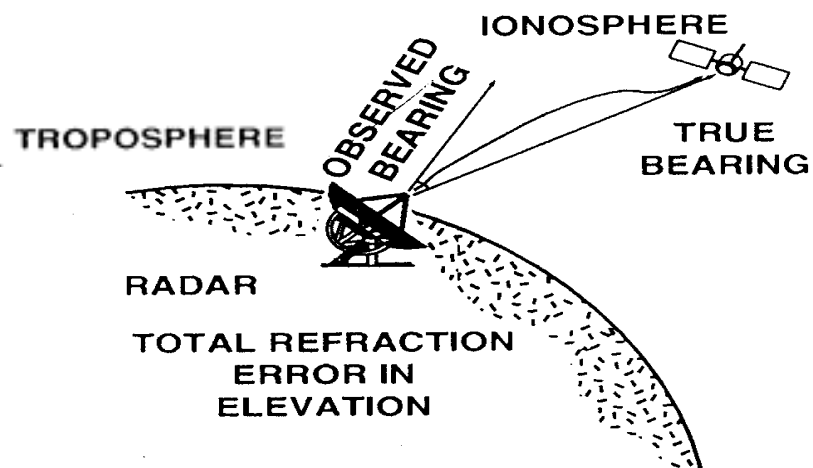


Illustration of Atmospheric Effects



Index of Refraction in the Ionosphere

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

$$X = \frac{\omega_N^2}{\omega^2} \quad Y = \frac{\omega_H}{\omega} \quad \omega_N = \left(\frac{N e^2}{\epsilon_0 m_e} \right)^{1/2} \quad \omega_H = \frac{e |B|}{m_e}$$

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.

Ionospheric Range Correction

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

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

<u>Range Delay</u>						
<u>TEC</u>	<u>S-Band</u>	<u>L-Band</u>	<u>UHF</u>	<u>VHF</u>	<u>Elev</u>	<u>Mapping Function</u>
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

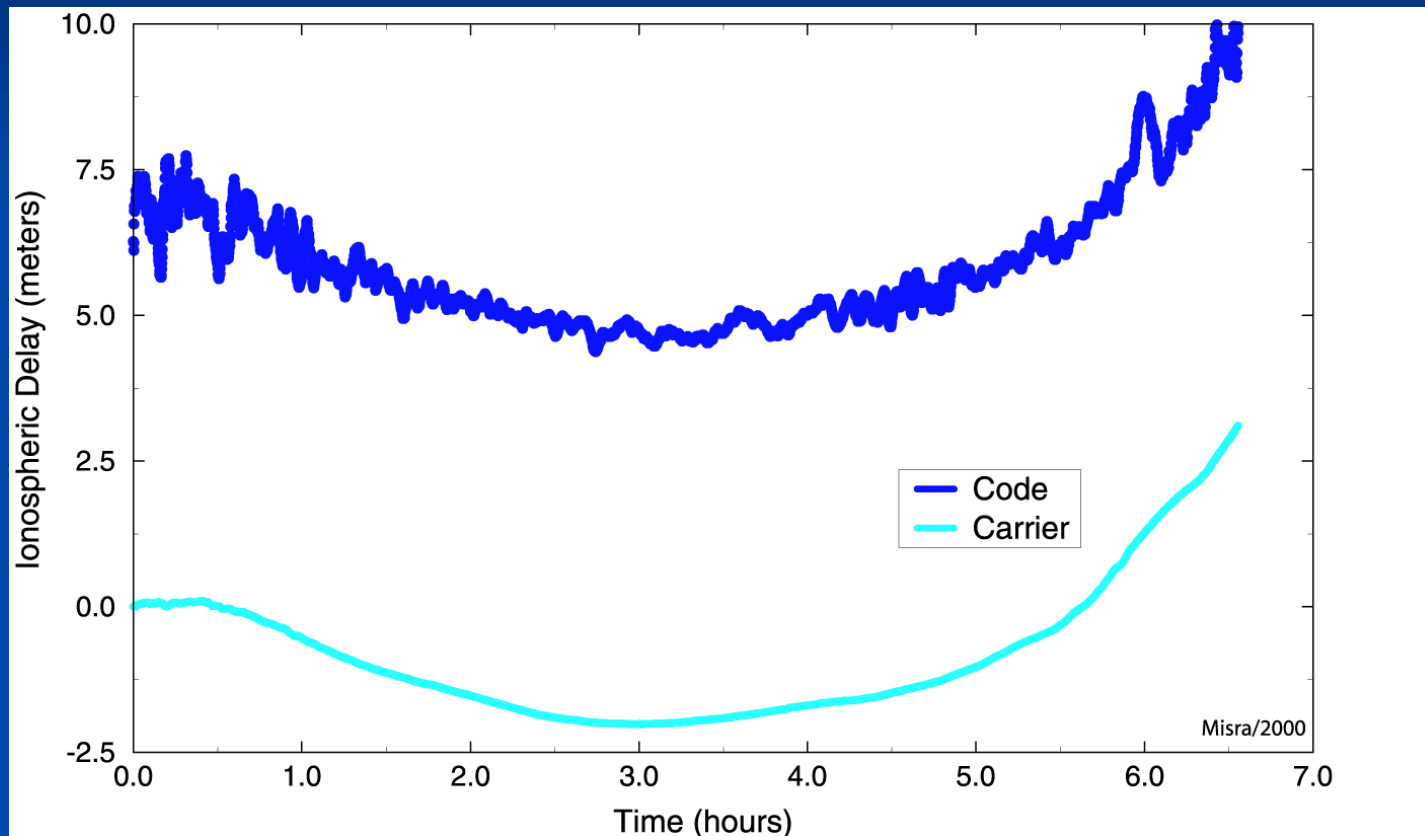
Ground-Based Receivers

- **Total Electron Content**
- **Scintillation Parameters: S_4 and σ_ϕ**

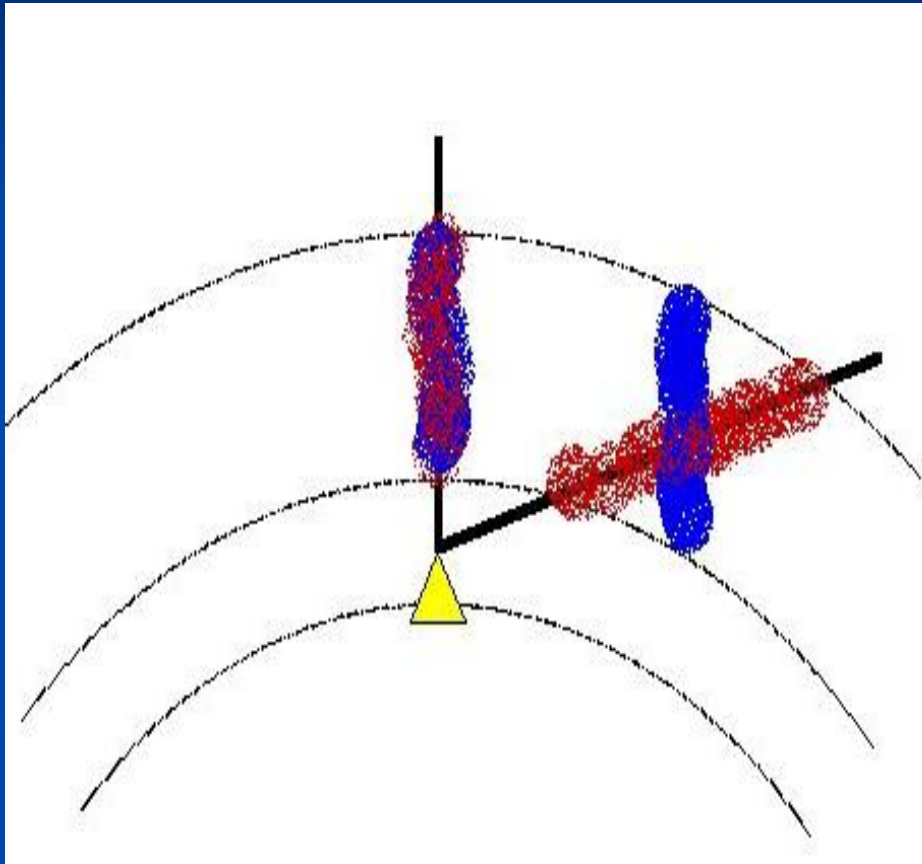
Space-Based Receivers

- **Electron Density Profiles**
- **Scintillation Parameters: S_4 and σ_ϕ**

Total Electron Content (TEC) Estimation Dual-Frequency Measurements



Problem 1: Mapping Function

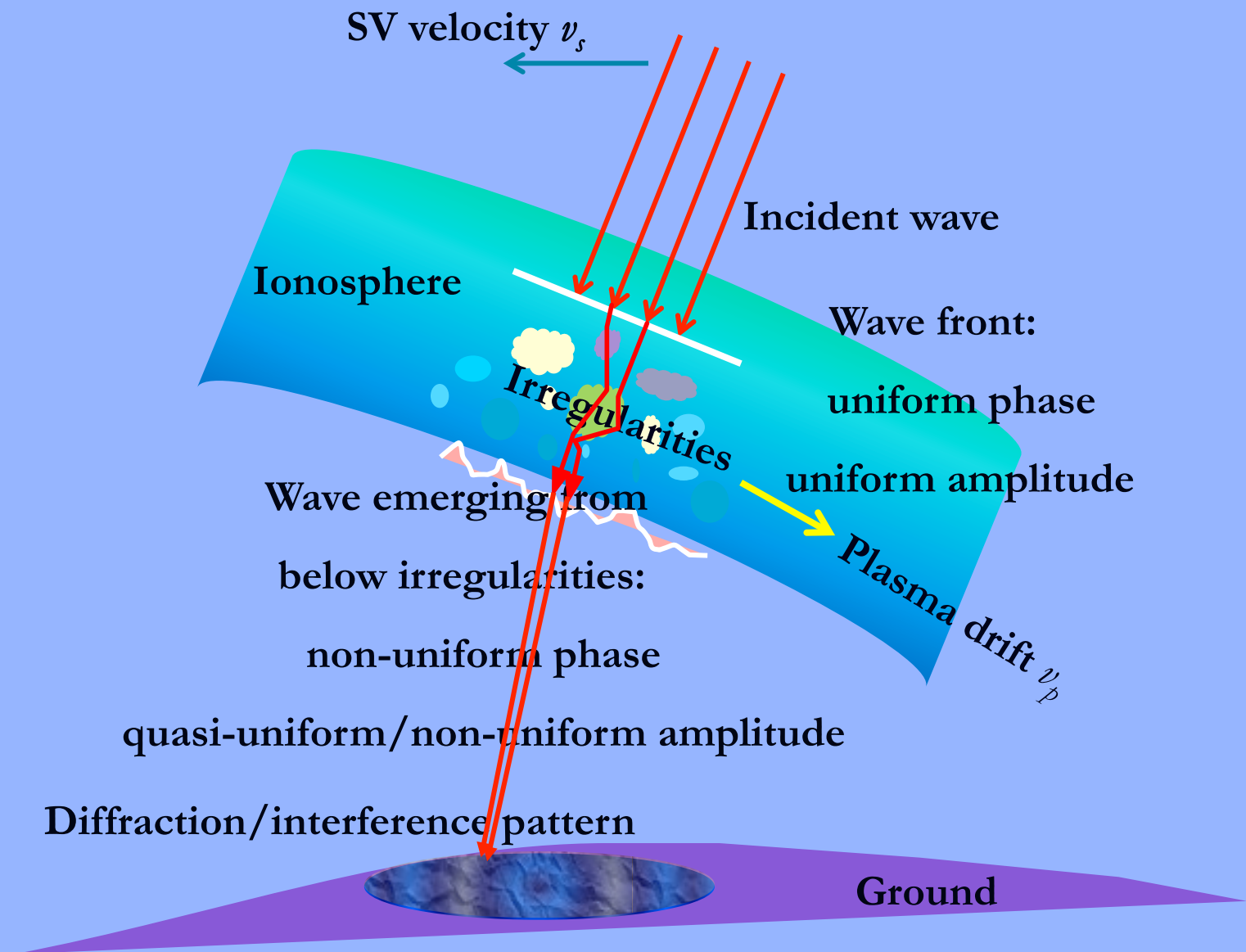


- Mapping function used to map TEC (line of sight) to Vertical TEC
- Assigns V-TEC to pierce point
- Function of Elevation
Range: $1 < Z < 3$

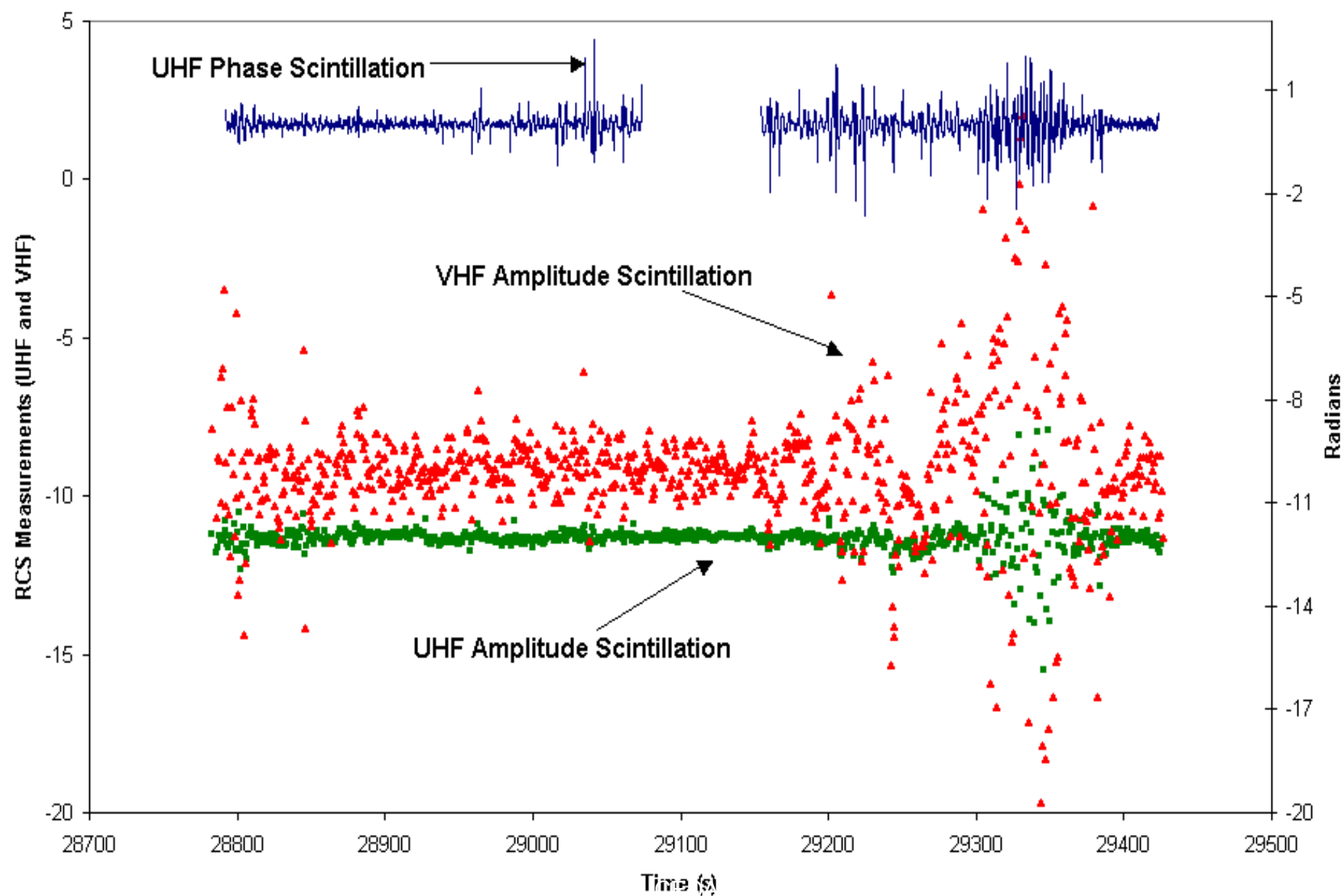
Problem 2: GPS Biases

- **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



Ascension Island Data Processing



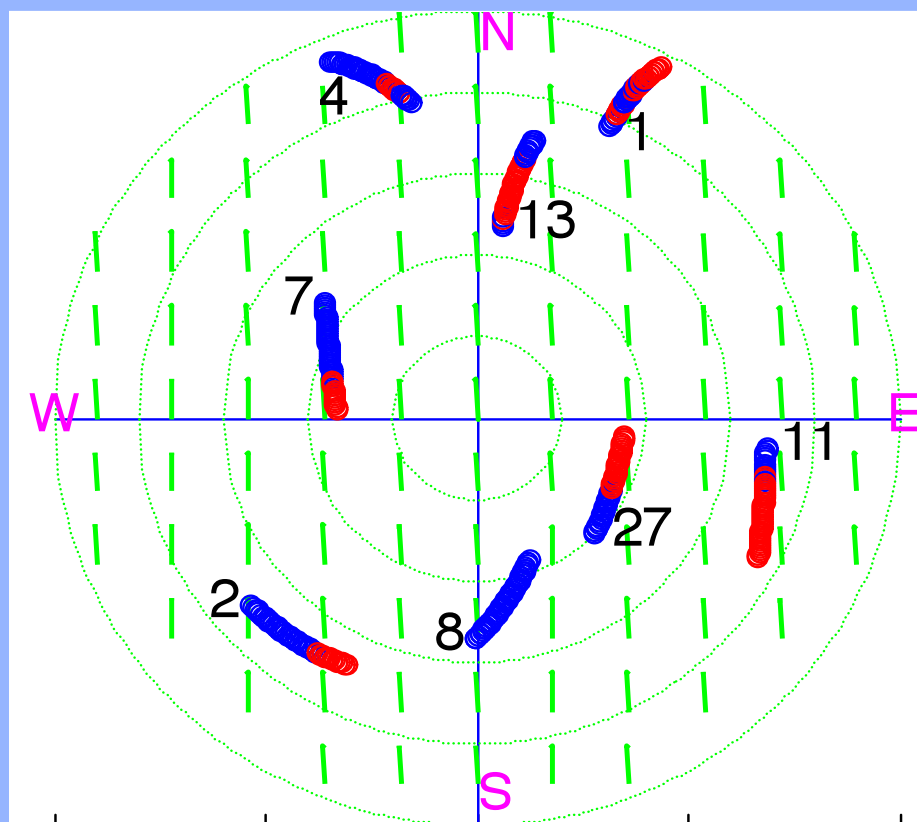
Lat: S7 °55' 20"

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

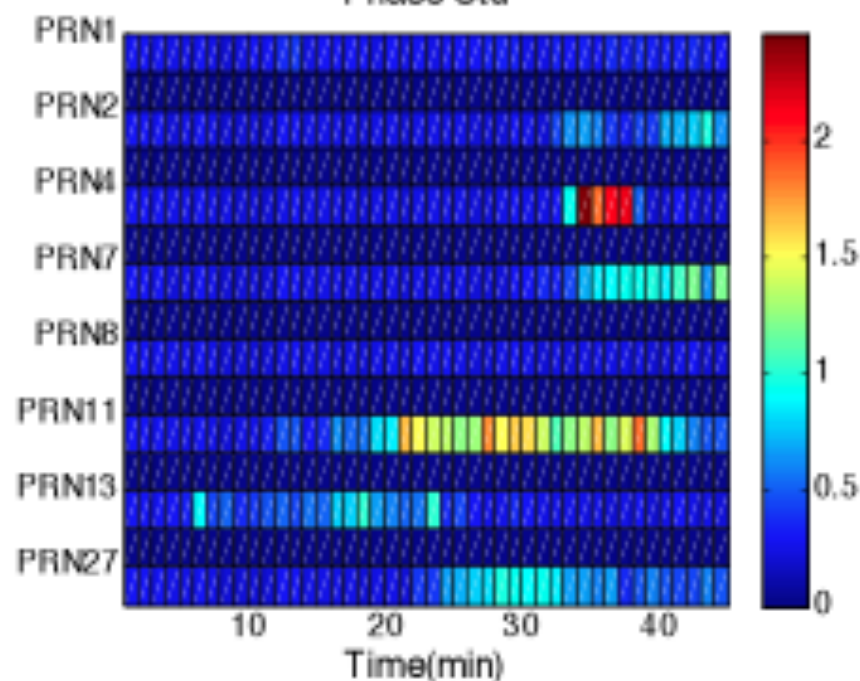
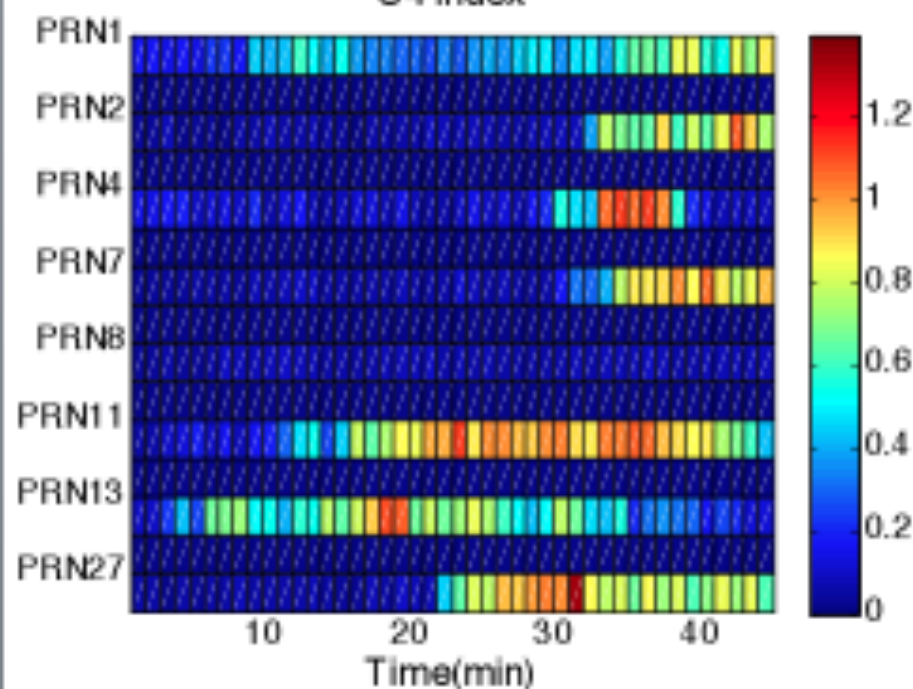
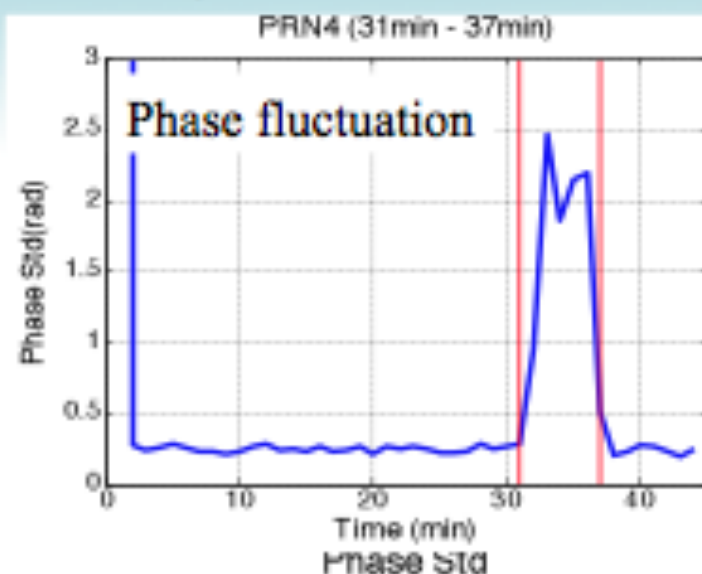
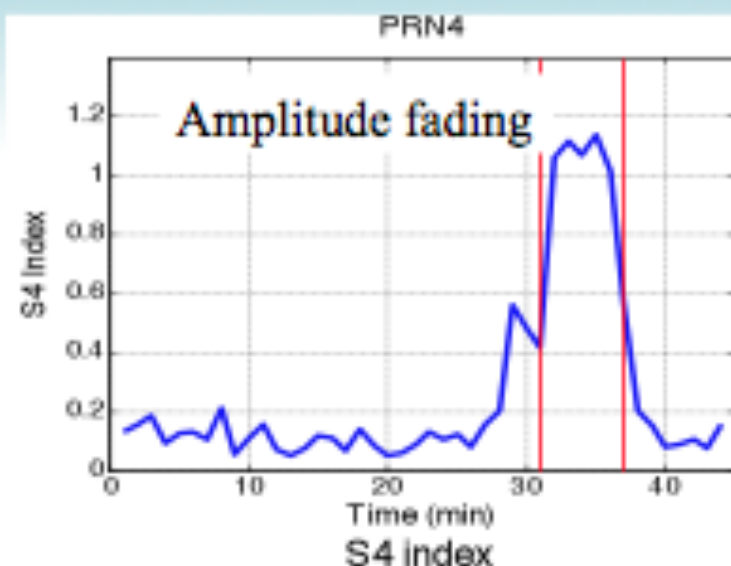
AFRL Hanscom, Ted Beach

NAVSYS DSR-100

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



Scintillation Indices: S_4 and σ_ϕ

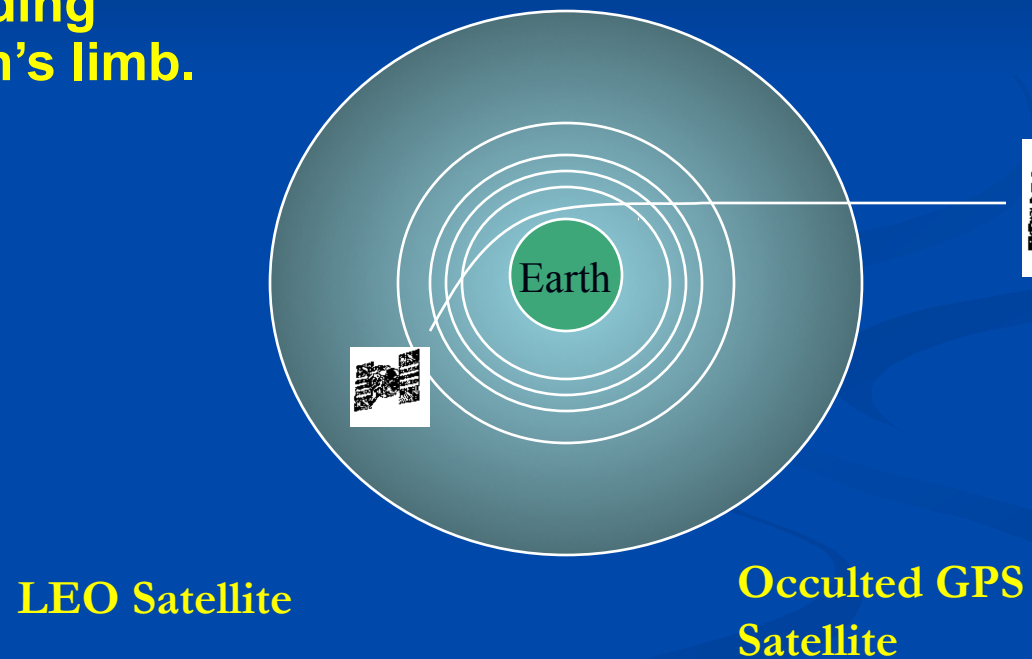


GPS Occultation

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.

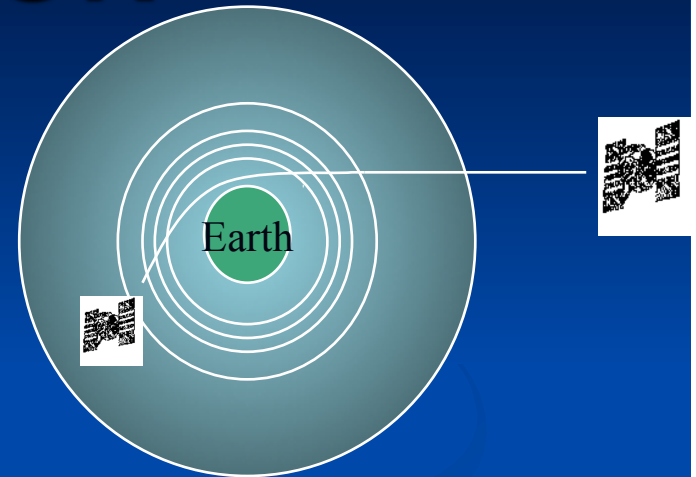
Orbit Altitudes :

LEO Satellite = 775 km



OCCULTATION

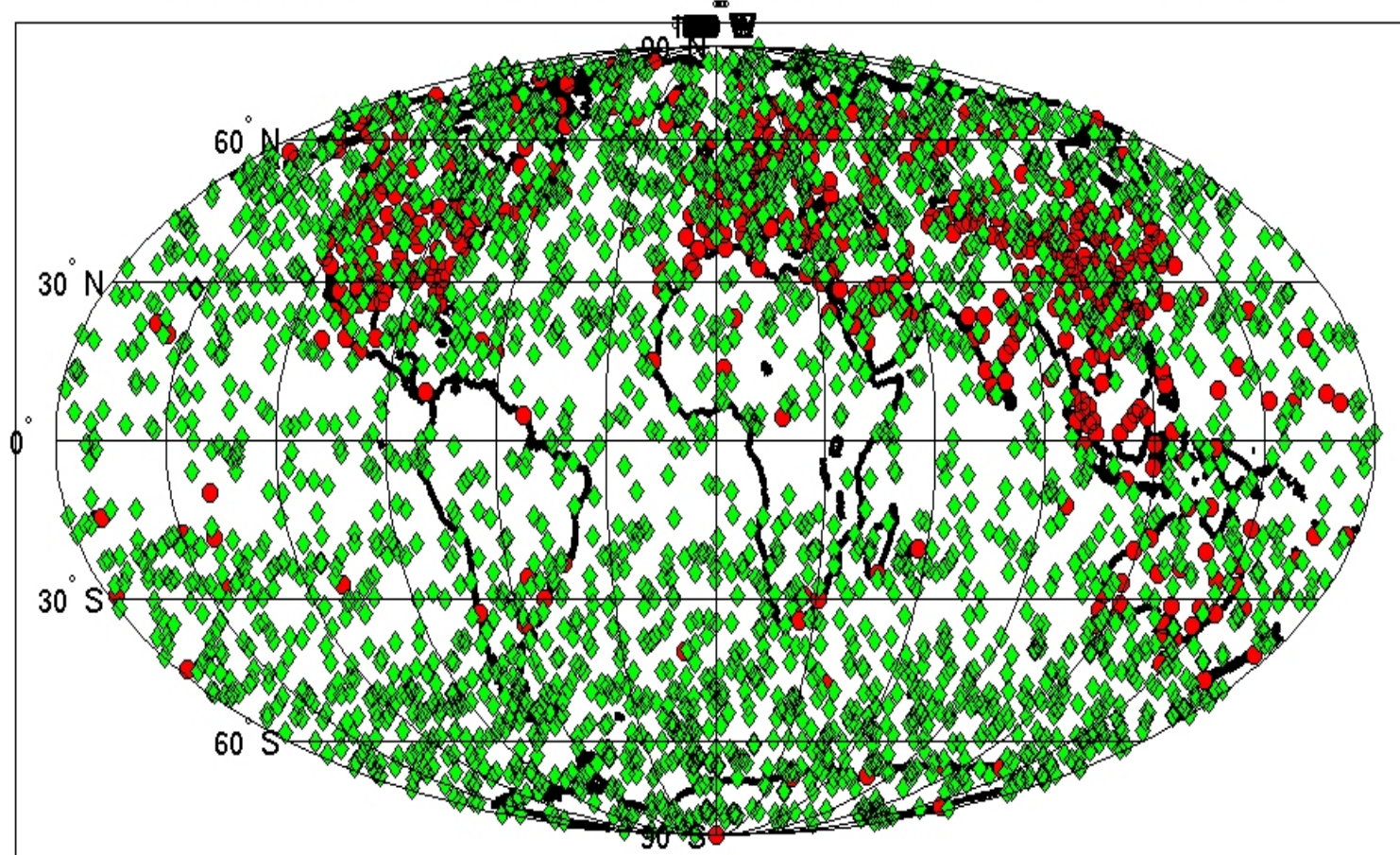
Received GPS frequency can be measured to an accuracy on the order of one part in 10^{13} . This translates to a bending accuracy of about 1 microdegree.



- 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.

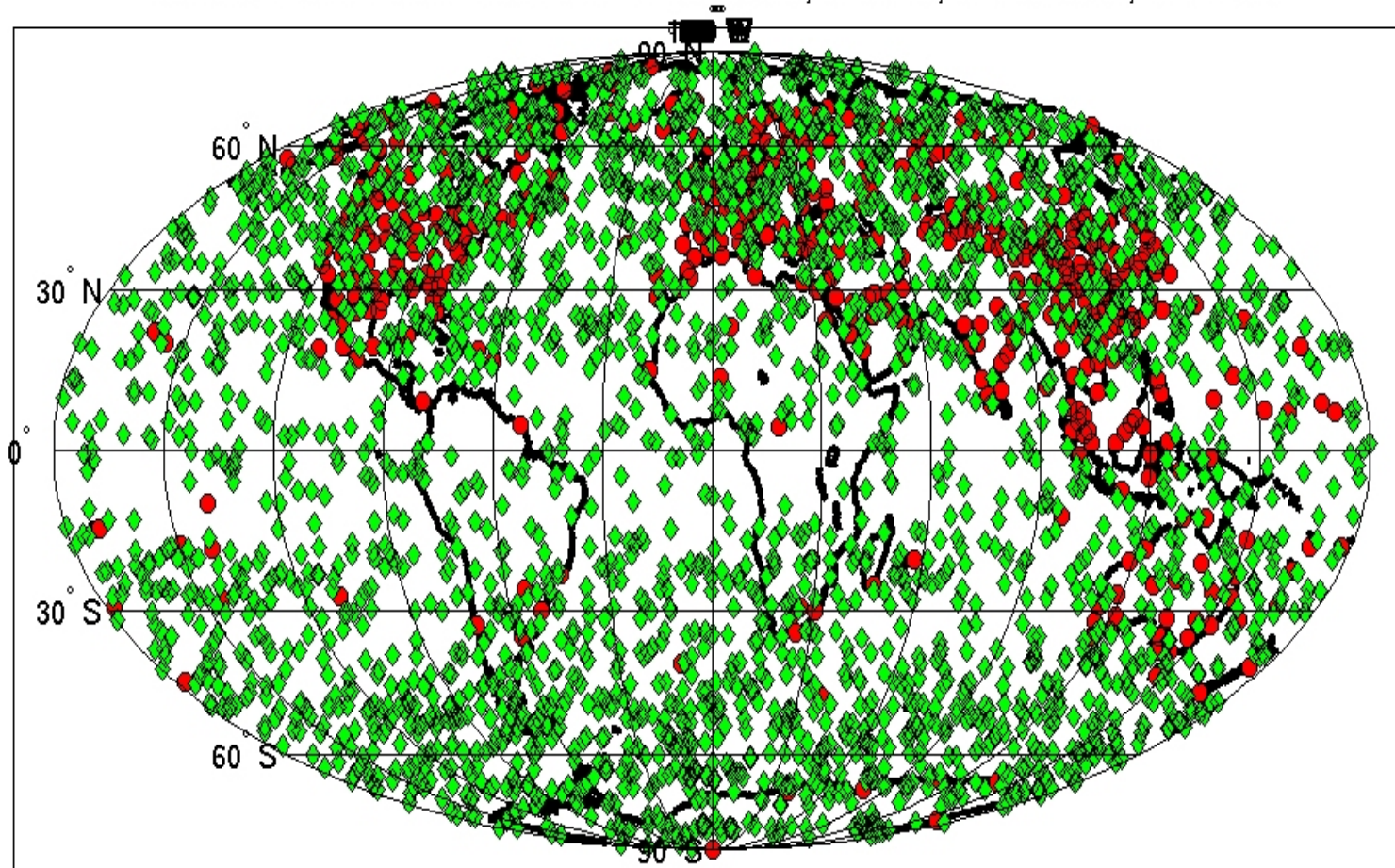
COSMIC sounding distribution in a day

Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs



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

Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs



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 TI4100 NAVSTAR Navigator

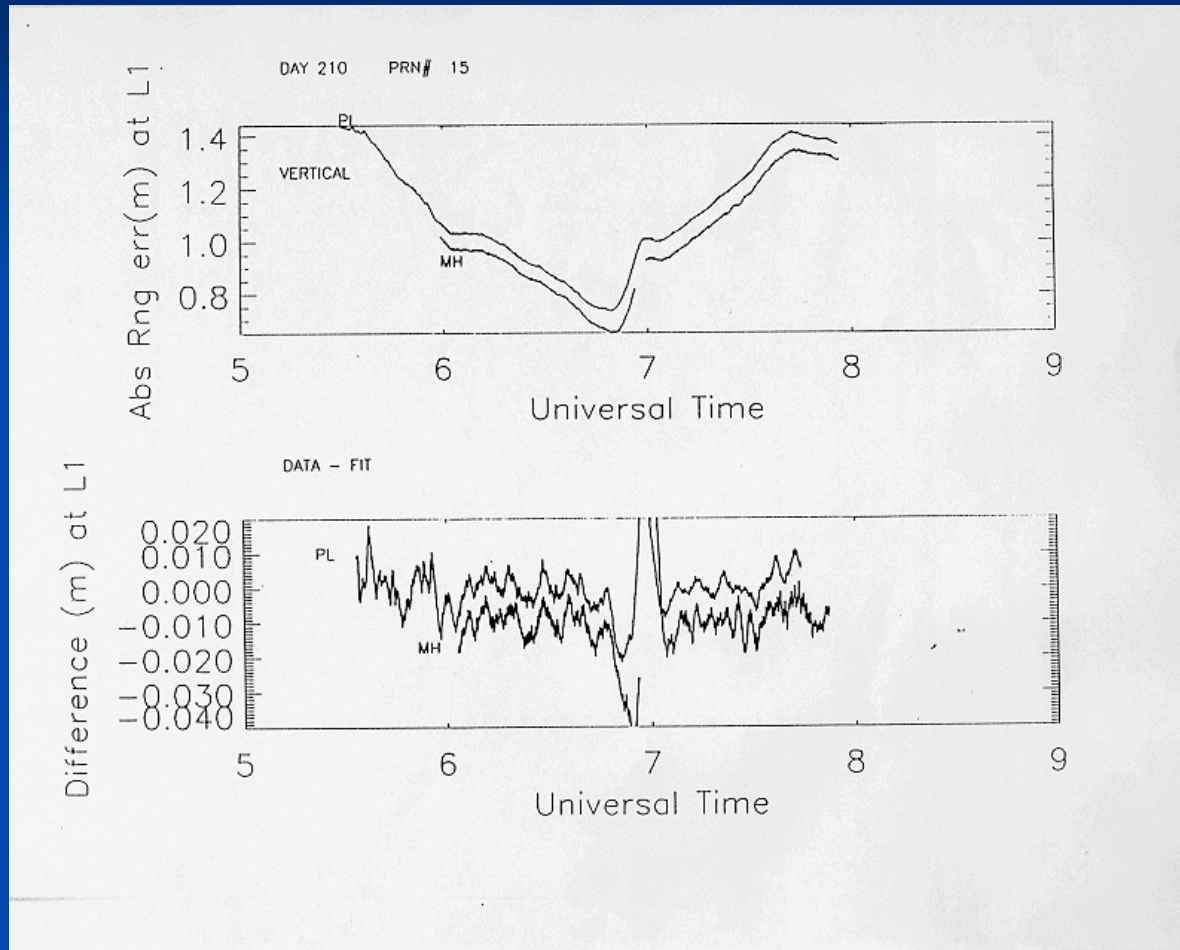
Owner's Manual



Historical TID Data 29 July 1991

Near Solar Maximum Geomagnetically Quiet Local Night

Characteristics of Nighttime MSTID with a 3% TECP





6/30/11

A. Coster, 2011 CEDAR/GEM tutorial

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6/30/11

A. Coster, 2011 CEDAR/GEM tutorial

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IGS: International GNSS Service

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

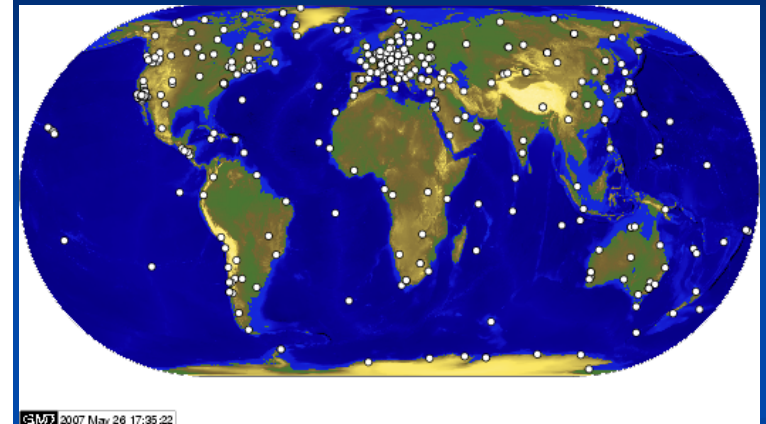
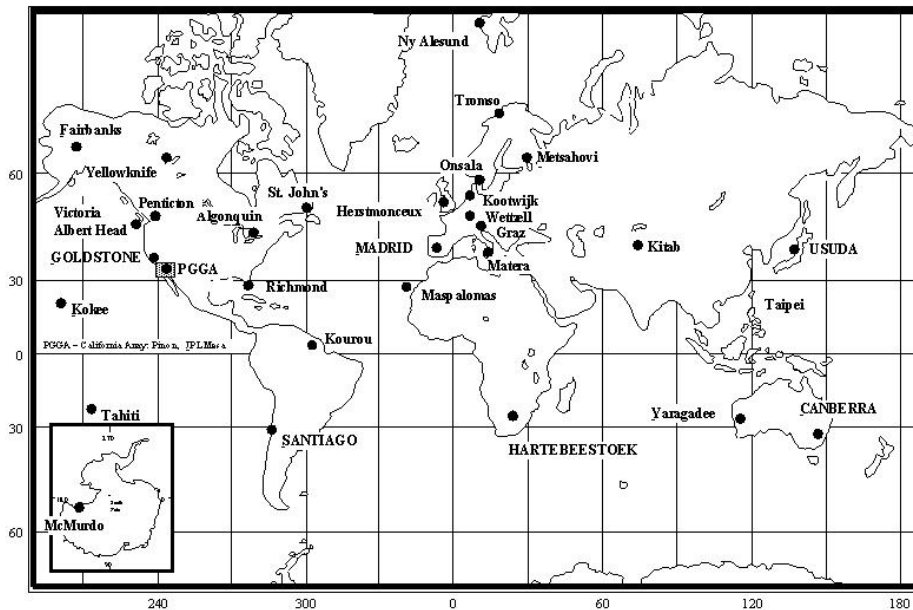
Early user of internet.

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

Station Locations for the IGS Pilot Campaign, 1992



IGS Network in 2007

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

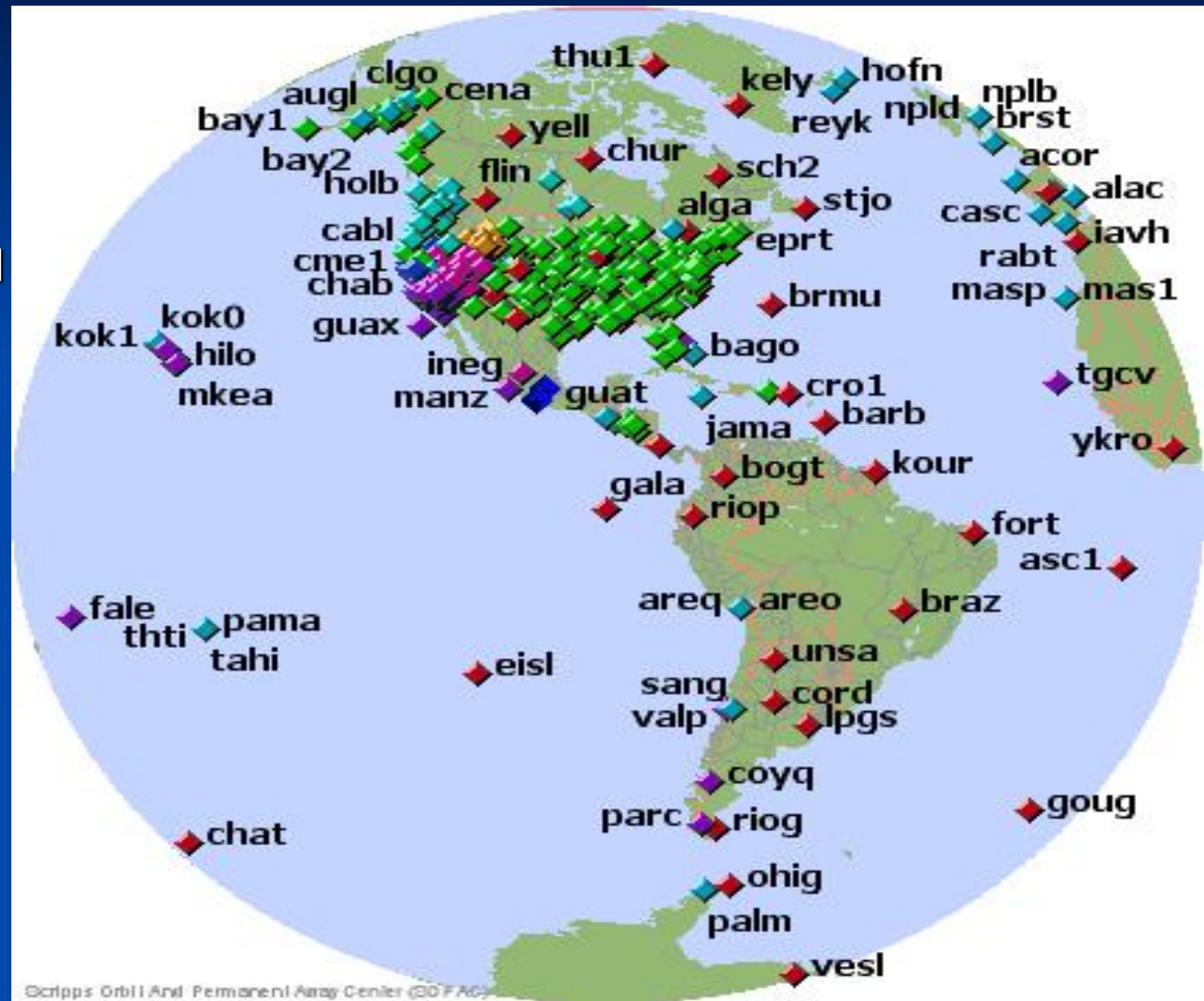
Based on this data JPL scientists first developed
mapping of TEC across the US

Across the US CEDAR/GEM tutorial

6/30/11

Wide Area Distribution of 'Raw' Information

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

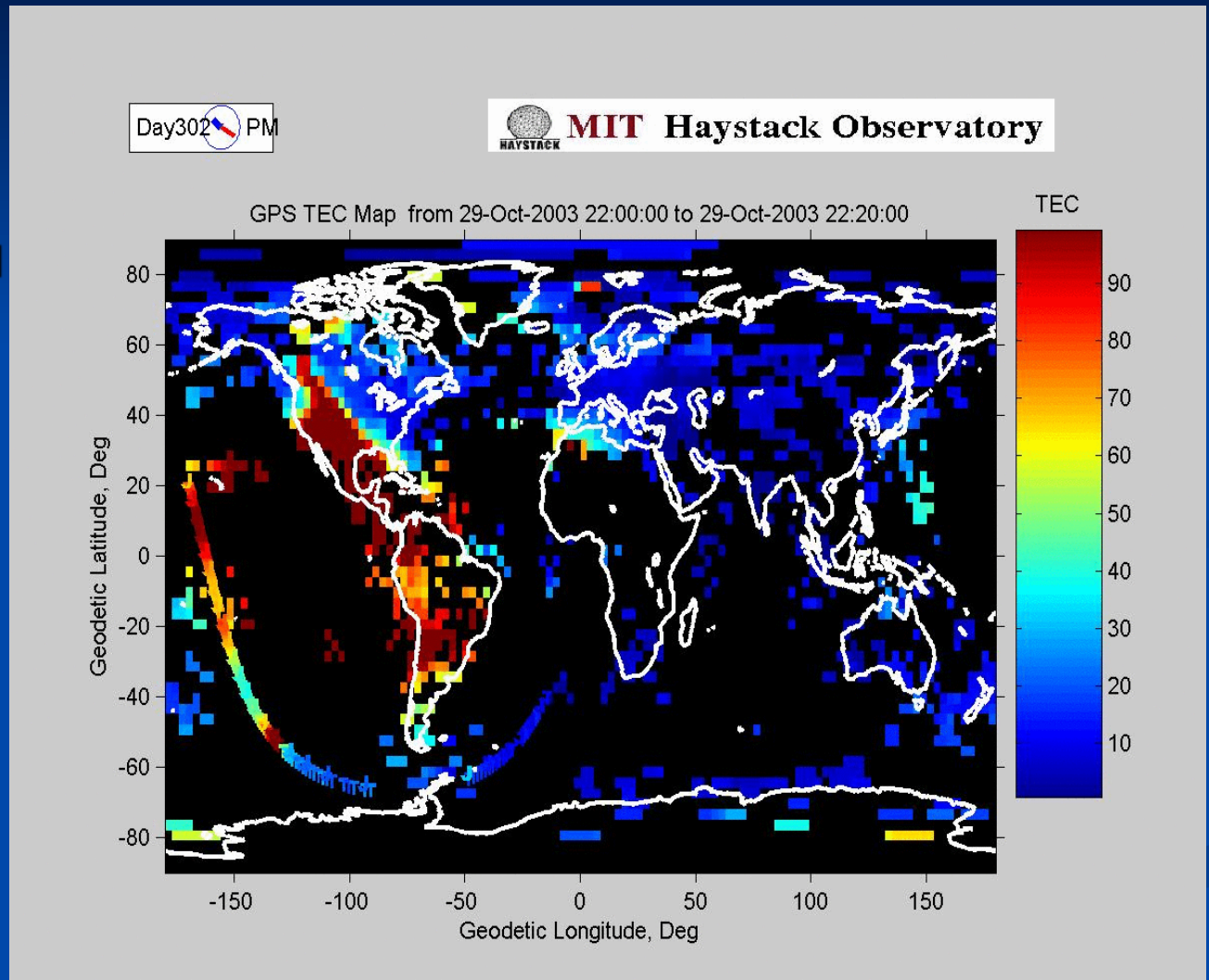


[Coster et al, 2003]

Wide Area Distribution of 'Raw' Information

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

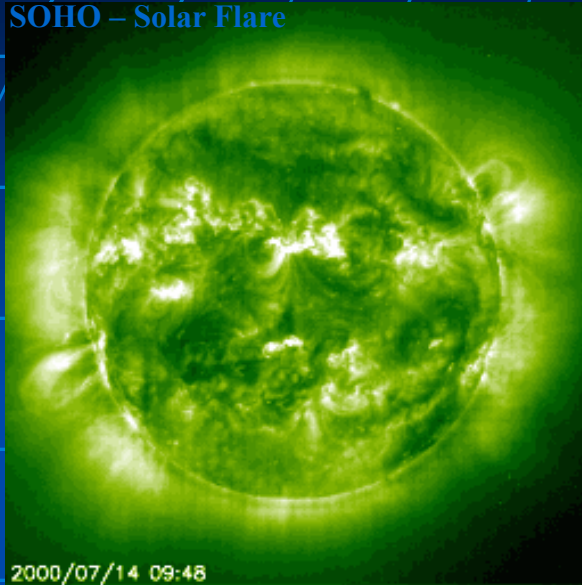
**Example :
Global GPS-derived
ionospheric mapping
during geomagnetic
disturbances**



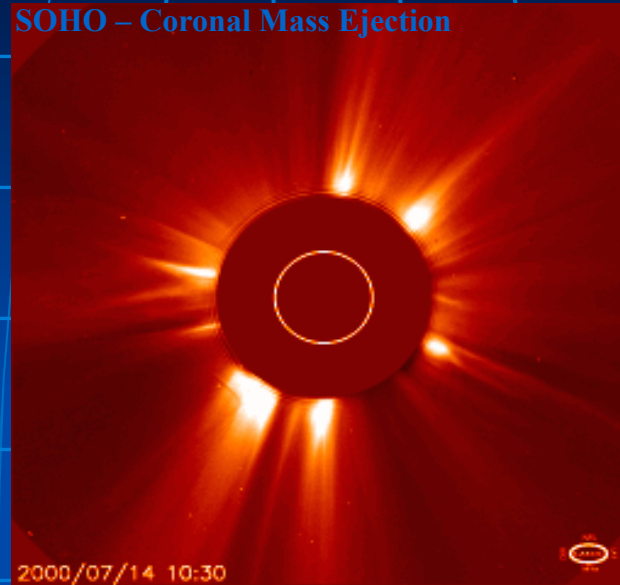
[Coster et al, 2003]

Solar Flare of 14 July 2000

SOHO – Solar Flare



SOHO – Coronal Mass Ejection



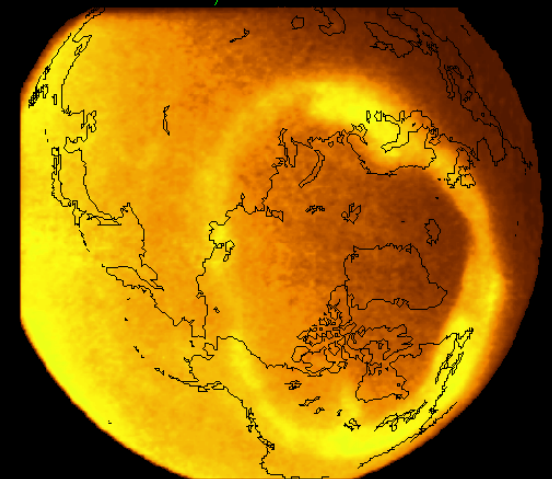
Solar Flare of 14 July 2000

Biggest Solar Storm in Nine Years

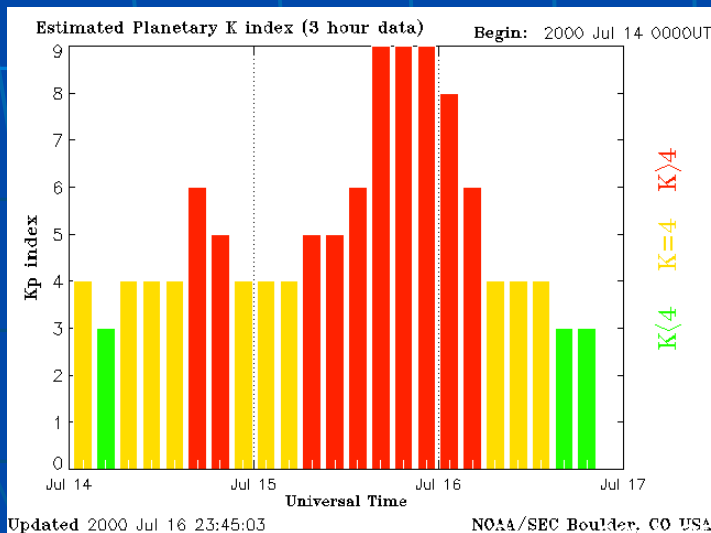
Caused very large magnetic storm and ionospheric effects



VIS Earth Camera
2000/198 00:50 UT



Visible Imaging System/POLAR
The University of Iowa

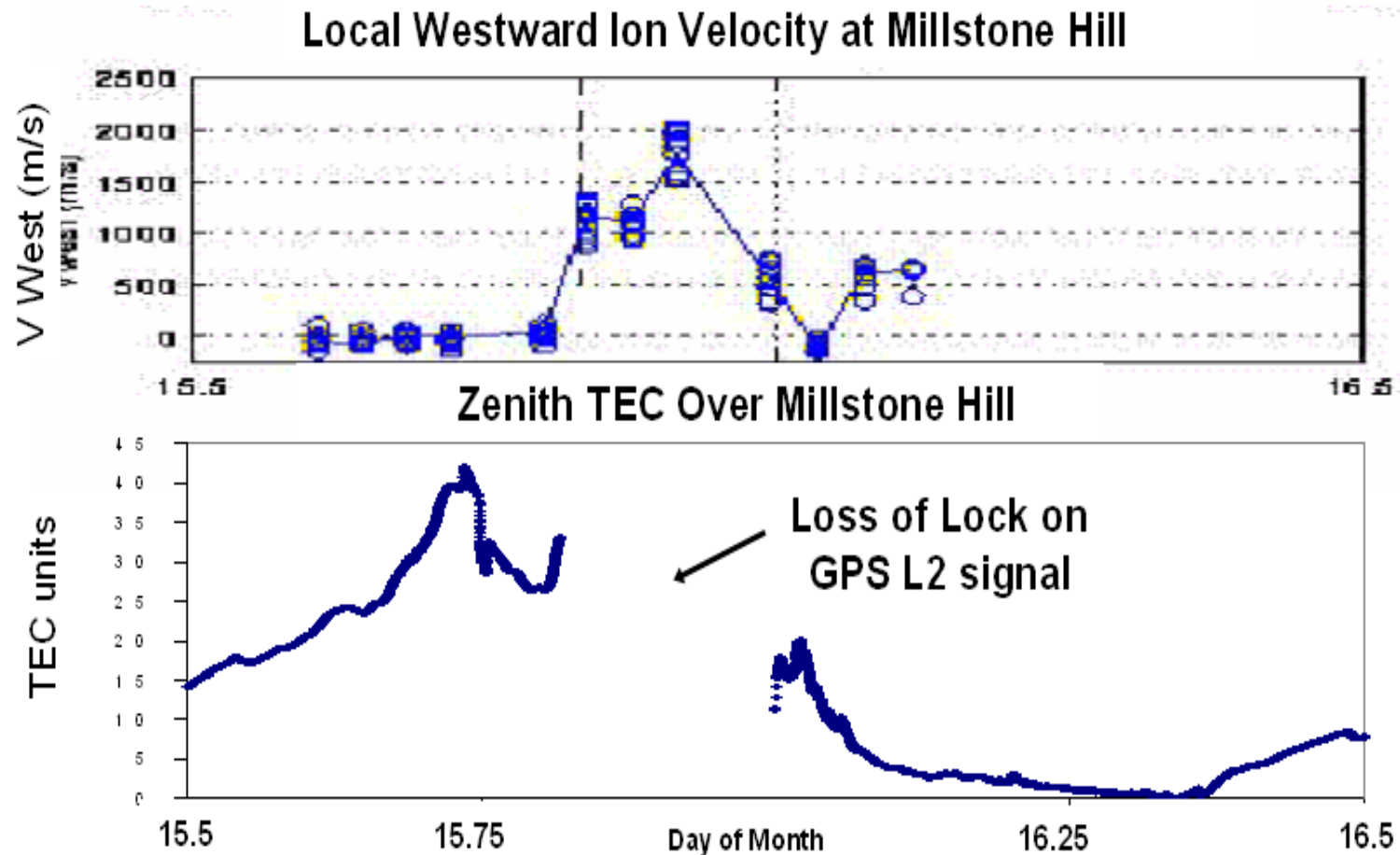


6/30/11

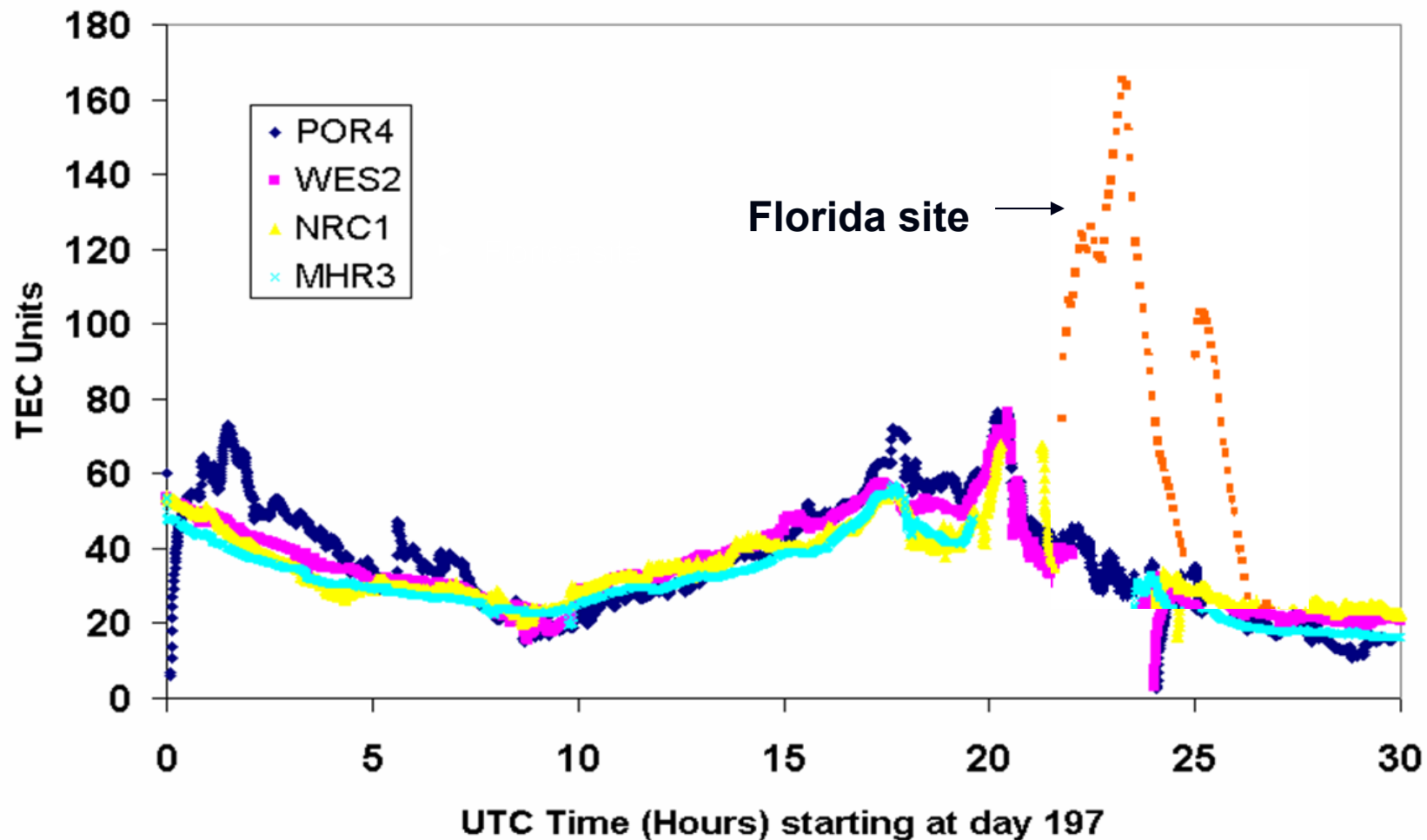
A. Coster, 2011 CEDAR/GEM tutorial

35

GPS Loss of Lock at Millstone Hill

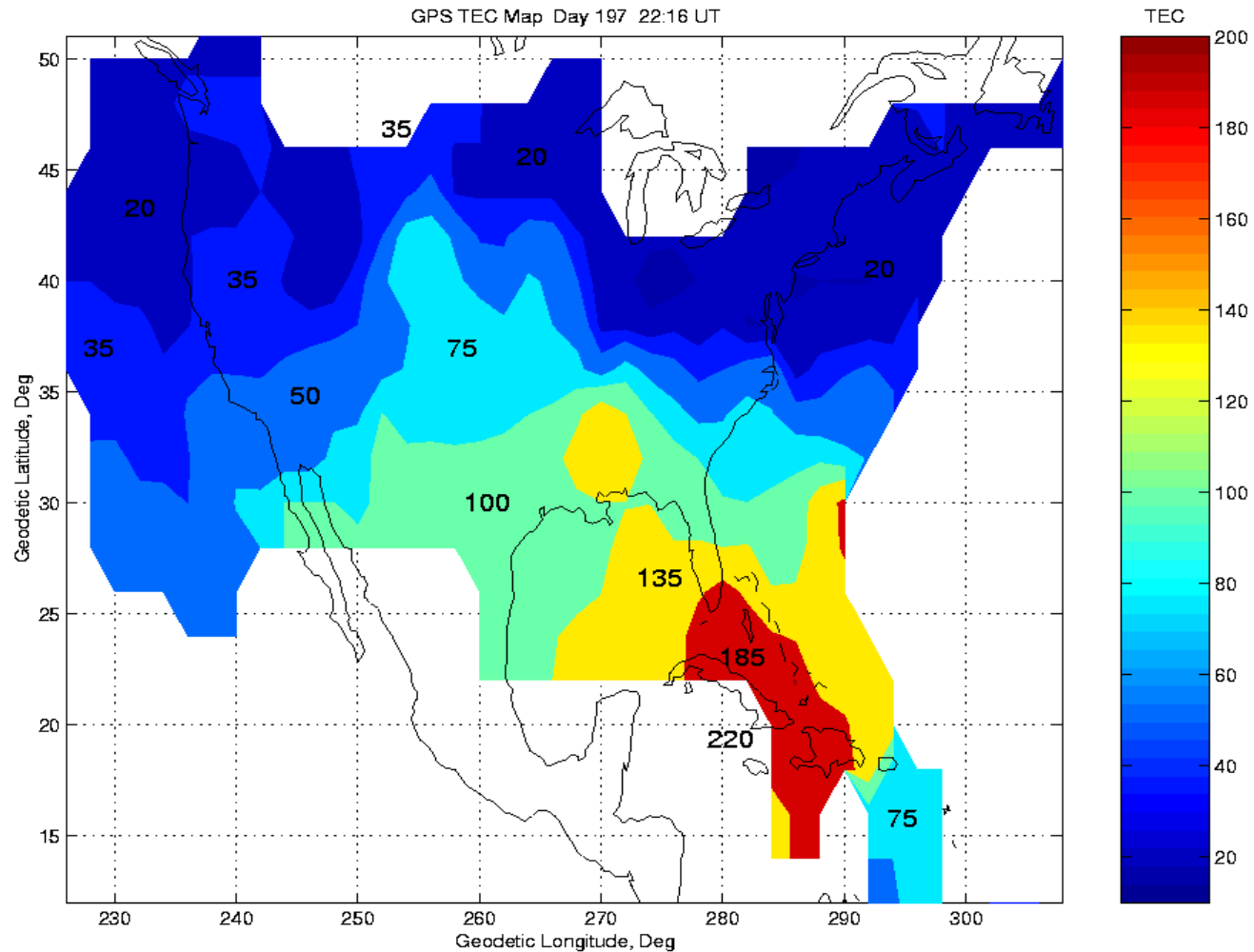


TEC Disturbances on 15 July 2000

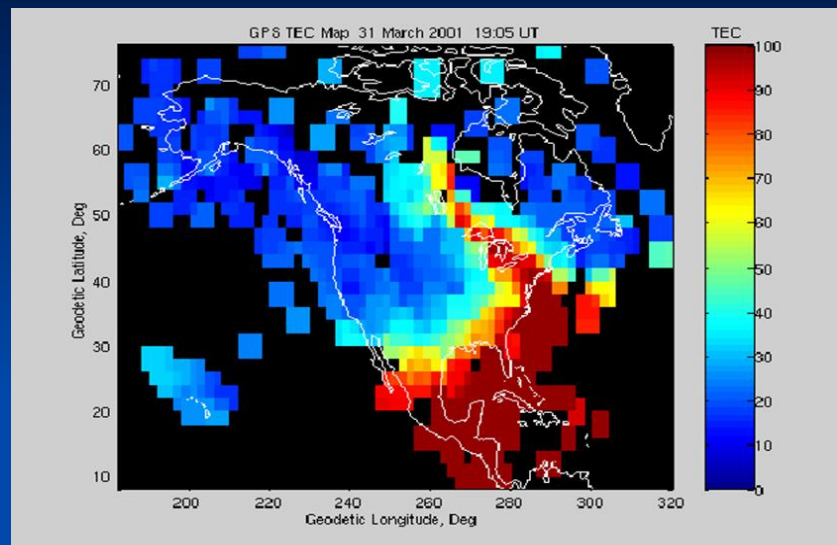


GPS Total Electron Content Map

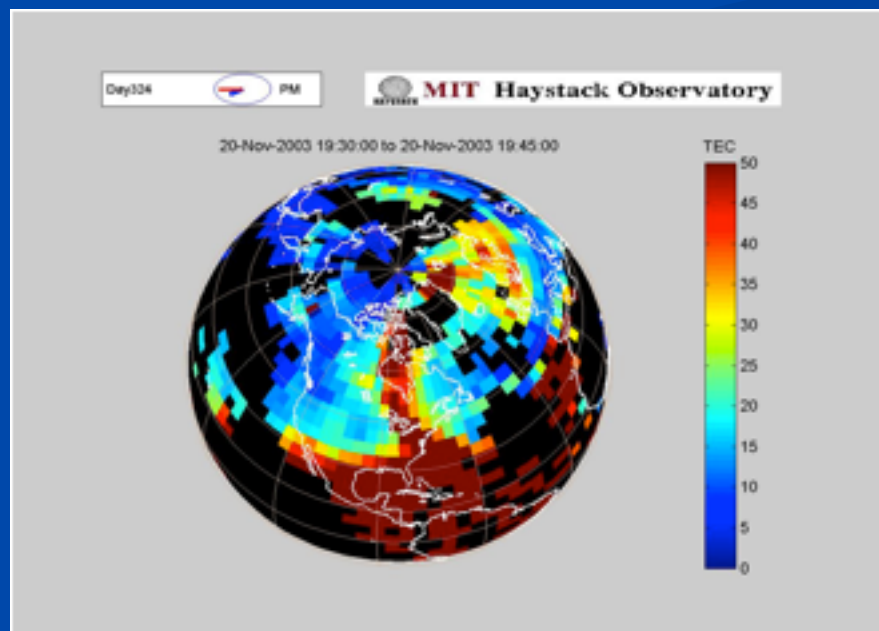
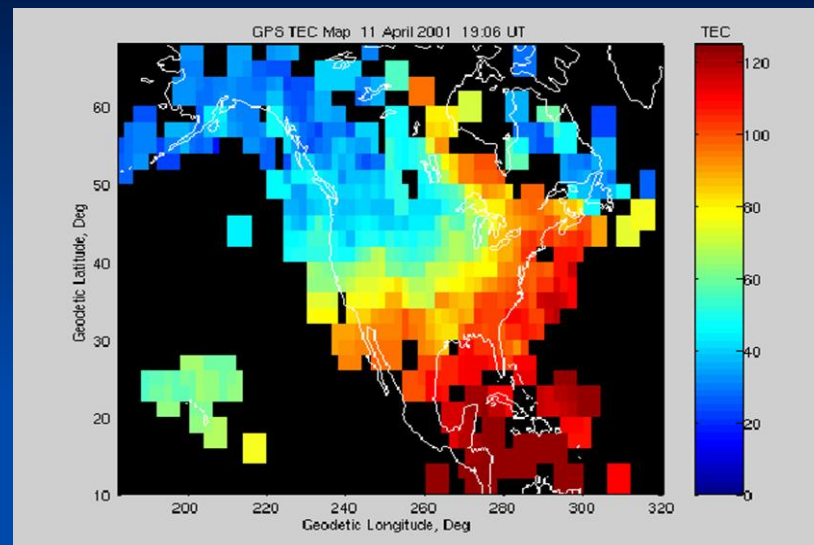
Illustration of Storm Enhanced Density



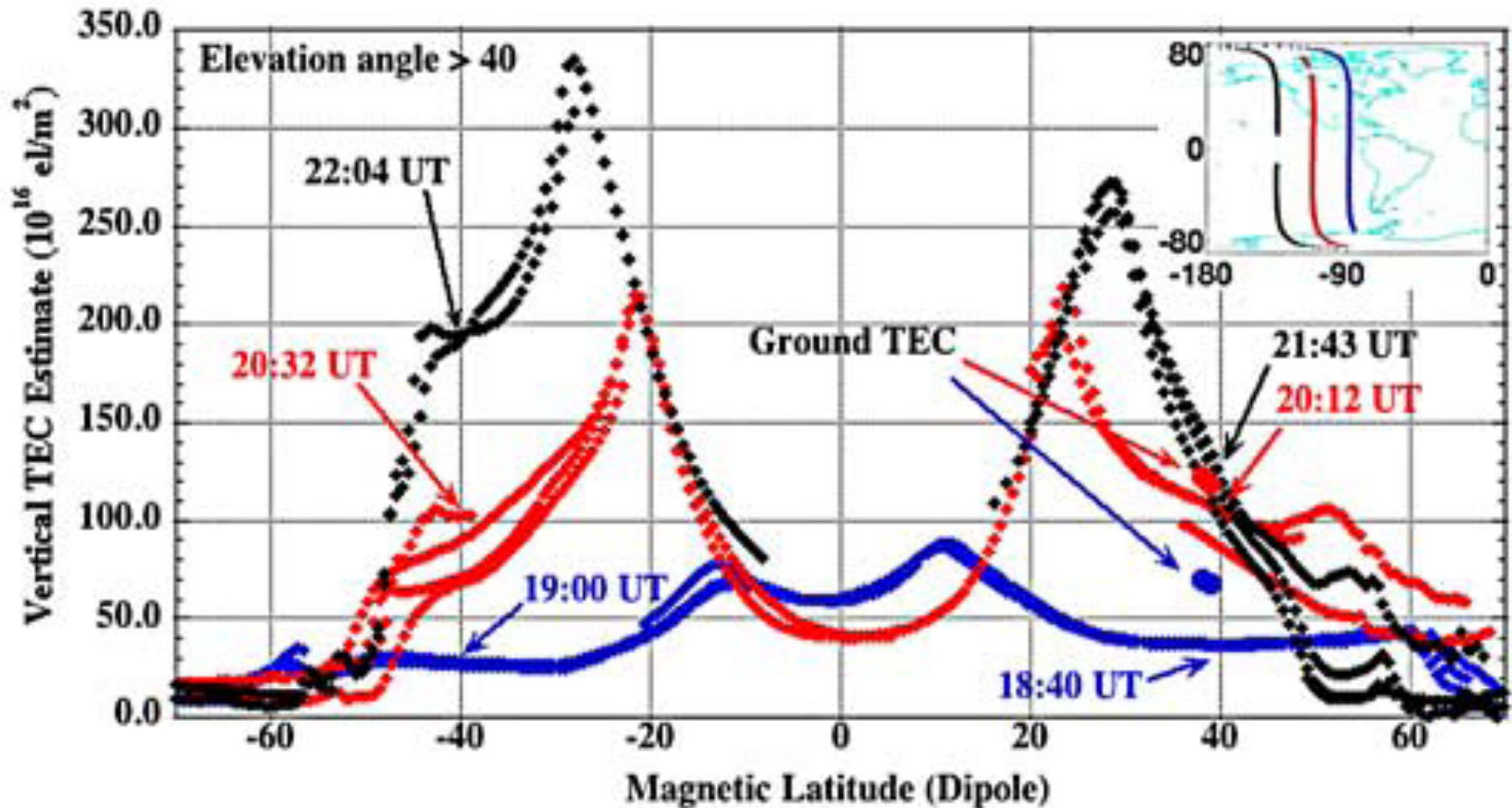
Day 90, 2001



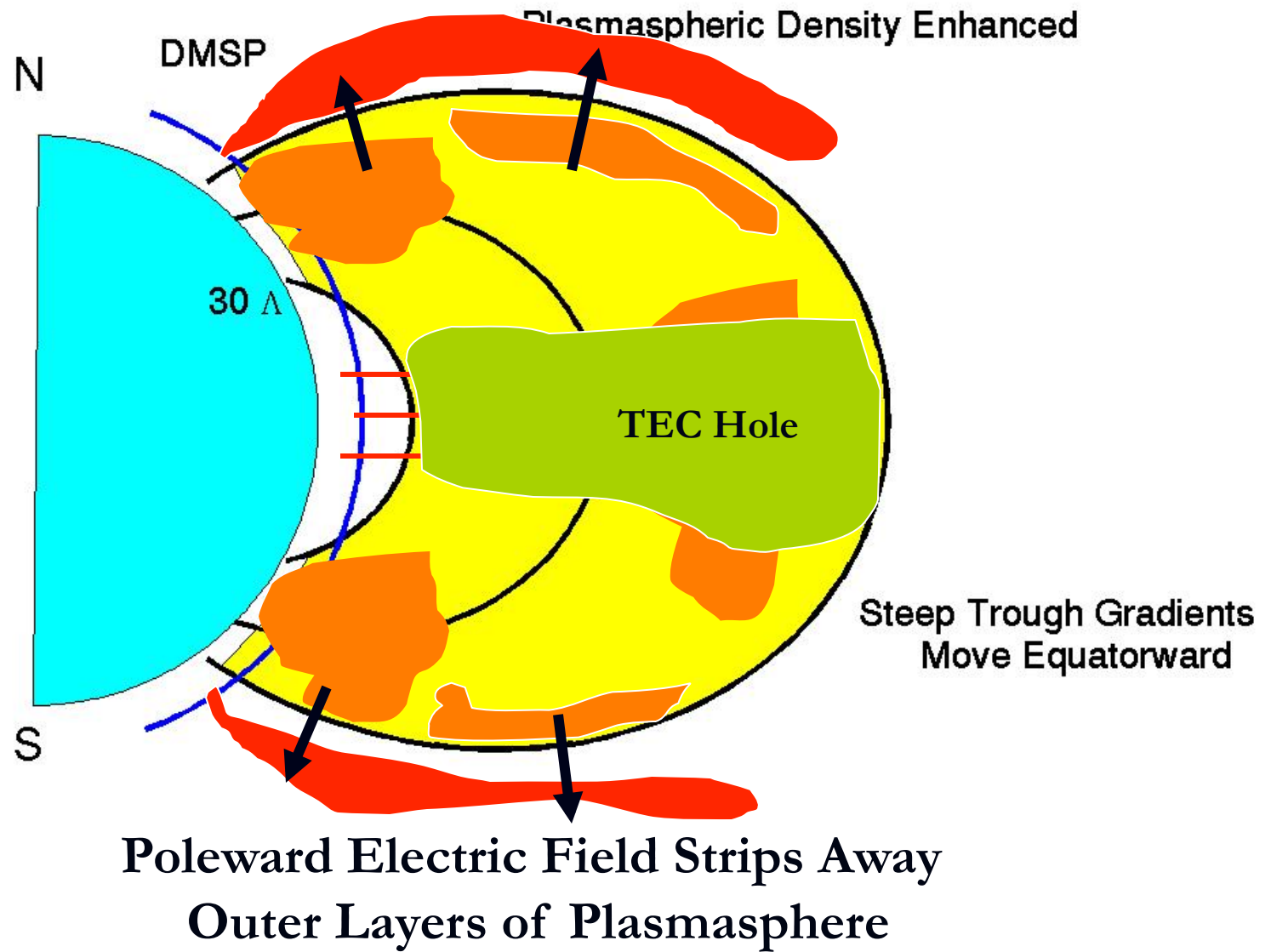
Day 101, 2001



Storm-time Appellton Anomaly



Effects of Penetration Electric Fields



Courtesy of J. Foster

Plasmaspheric Tails and Storm Enhanced Density

Foster et al., 2002, GRL

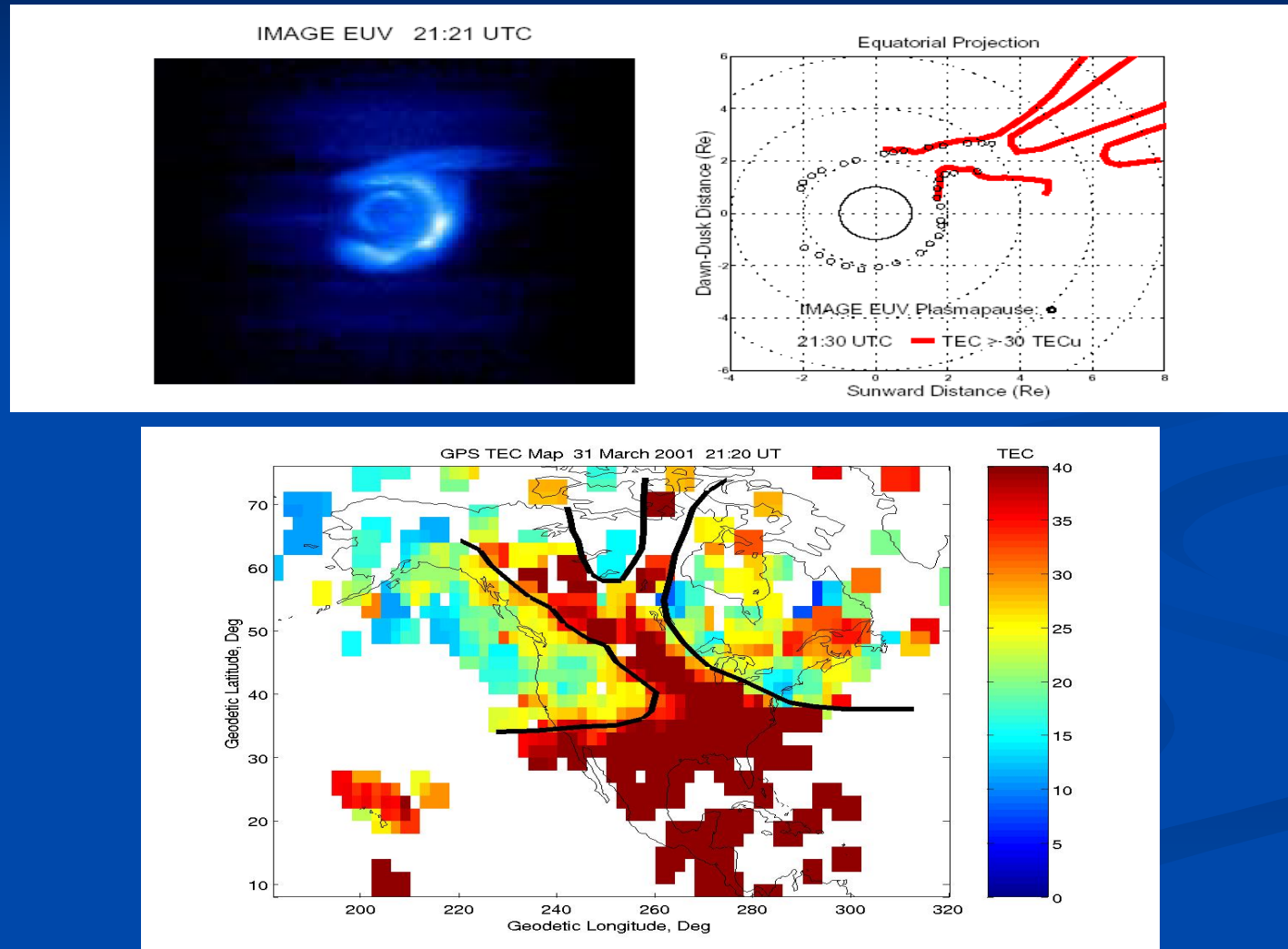
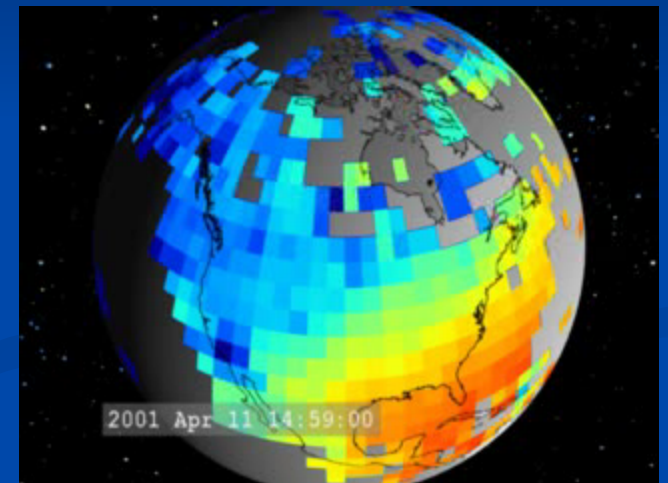
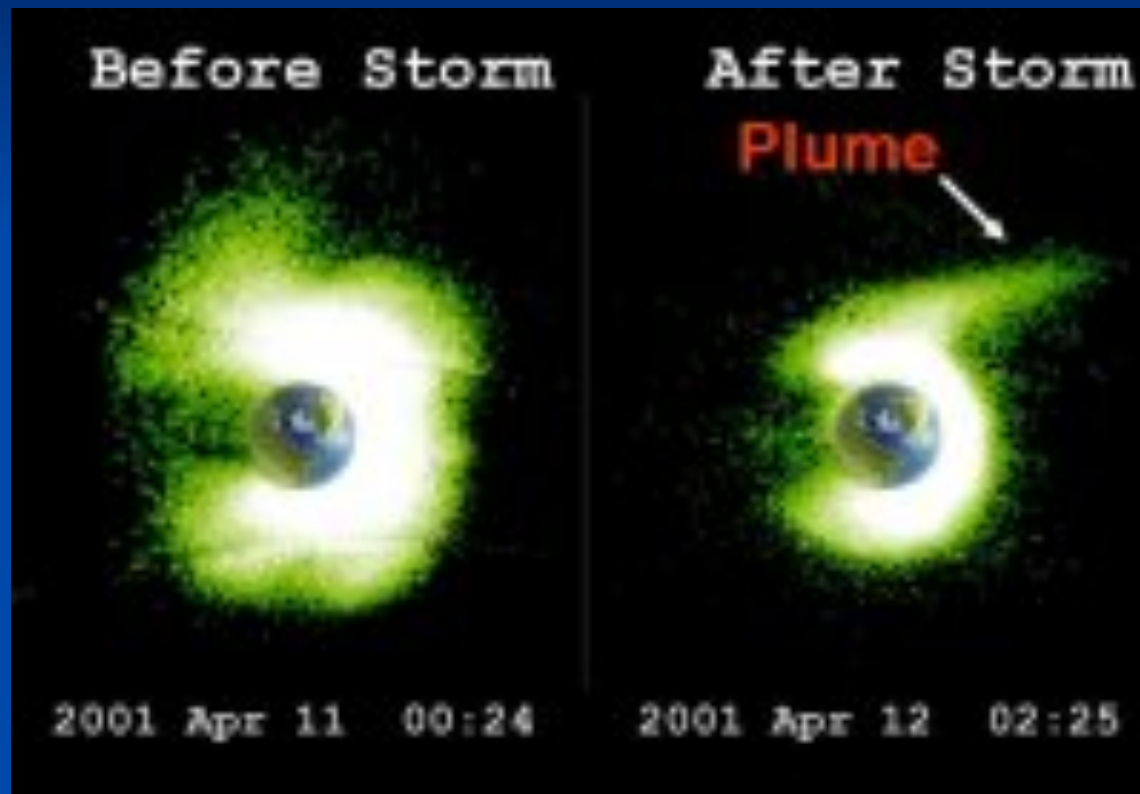
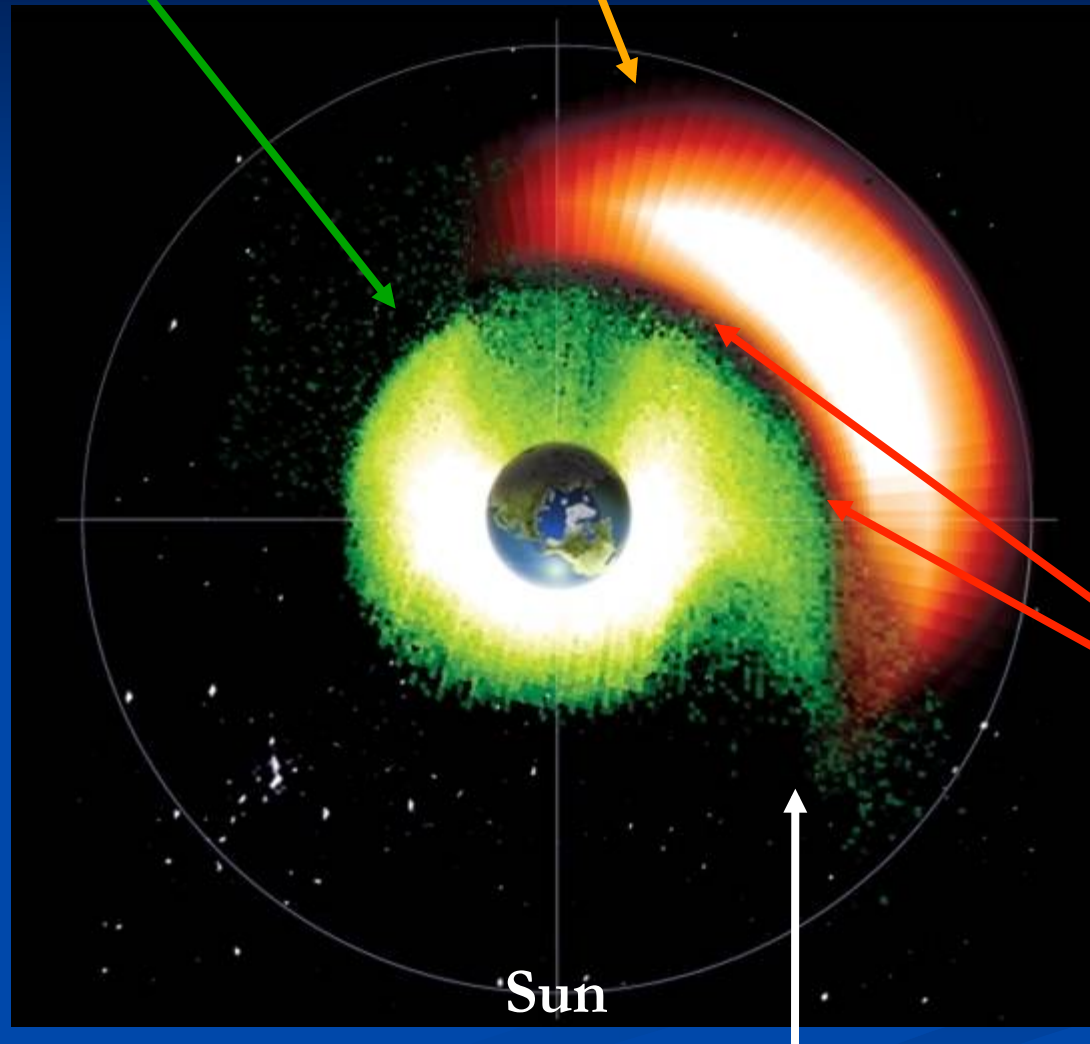


IMAGE Data of Plasmasphere



Plasmasphere / Ring Current Interactions



(Merged image courtesy J. Goldstein)
6/30/11

A. Coster, 2011 CEDAR/GEM tutorial

Outline

ABC's of GPS

Some history of measuring the
ionosphere with GPS

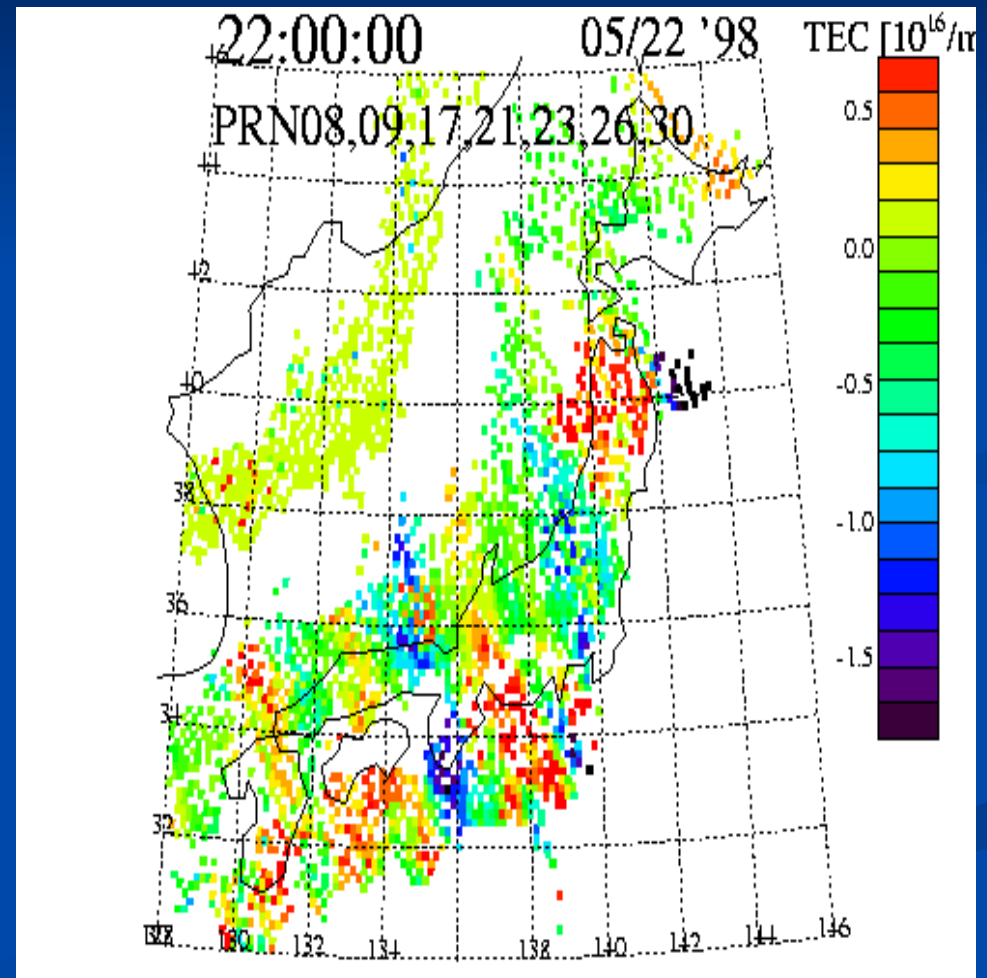
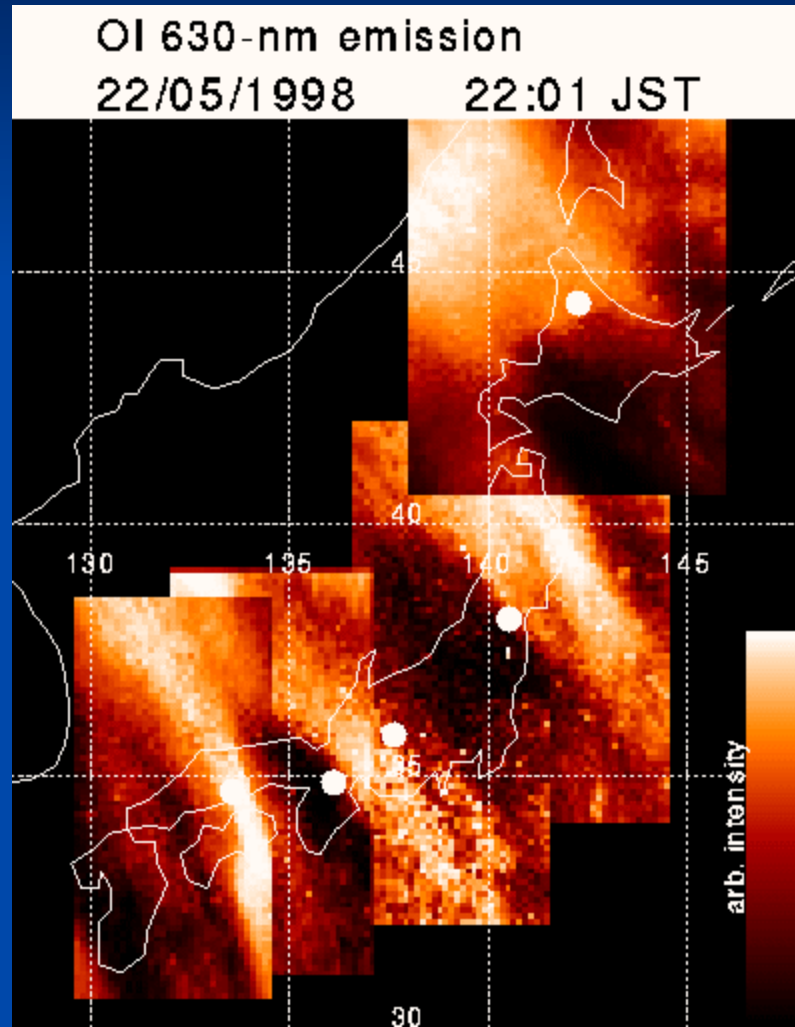


IT Coupling – GPS

MI Coupling – GPS

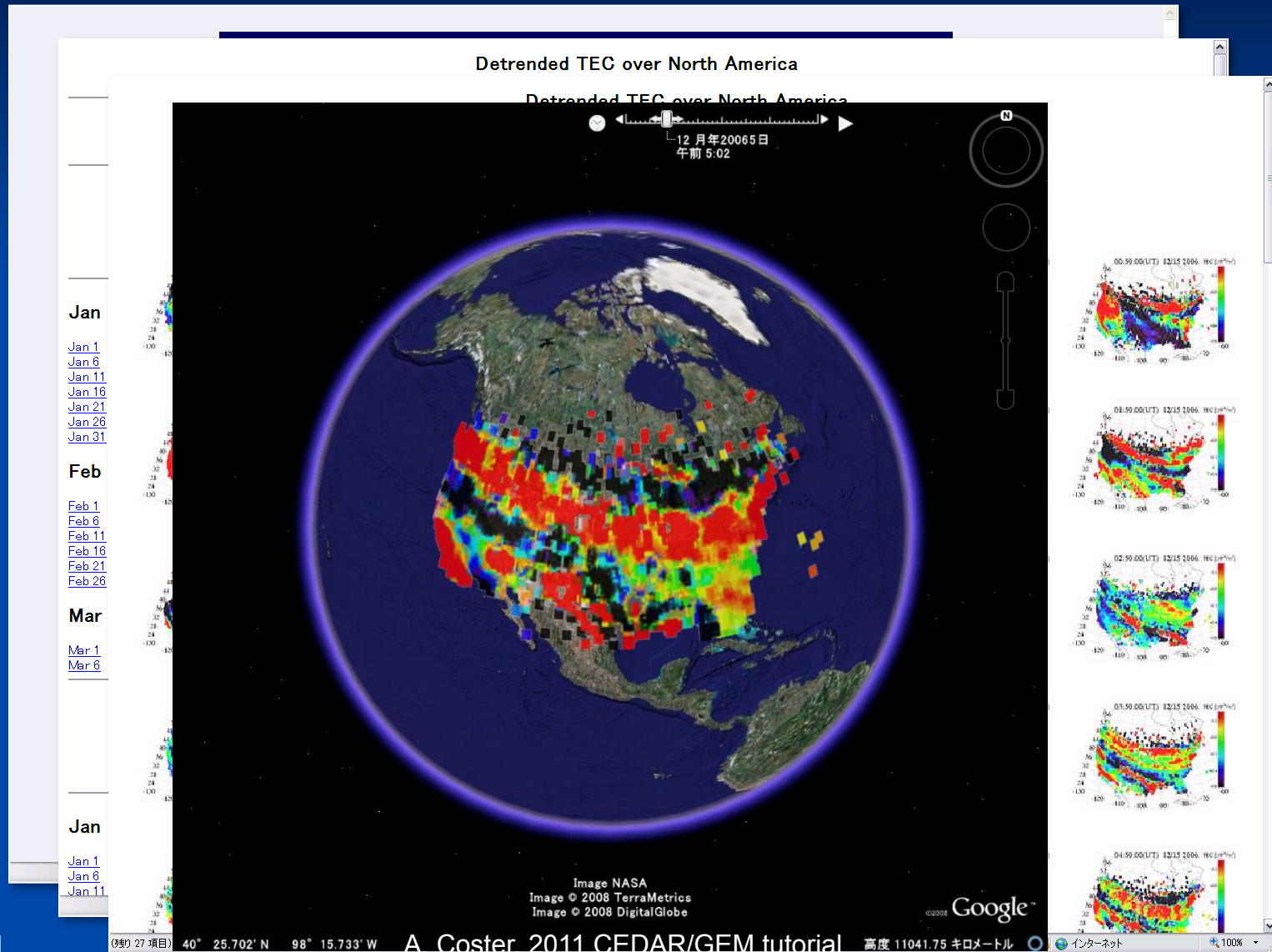
What's on the horizon

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/>

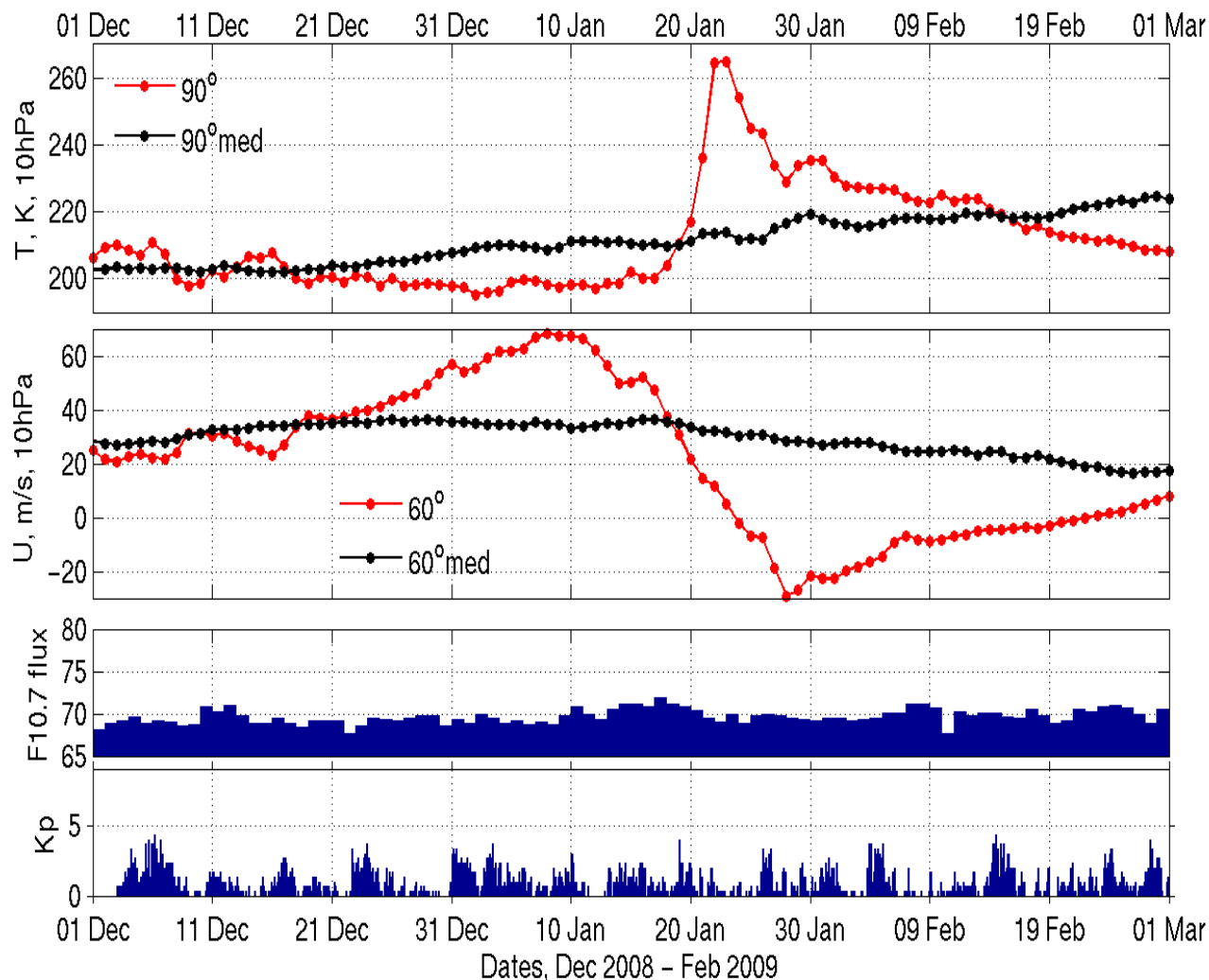


**The following movie is to show
that people have been
concerned with the stratosphere for a
long time ...**

Zombies in the Stratosphere

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

Sudden Stratospheric Warming and Solar Parameters [Jan 2009]



Stratospheric
Temperature over the
Arctic

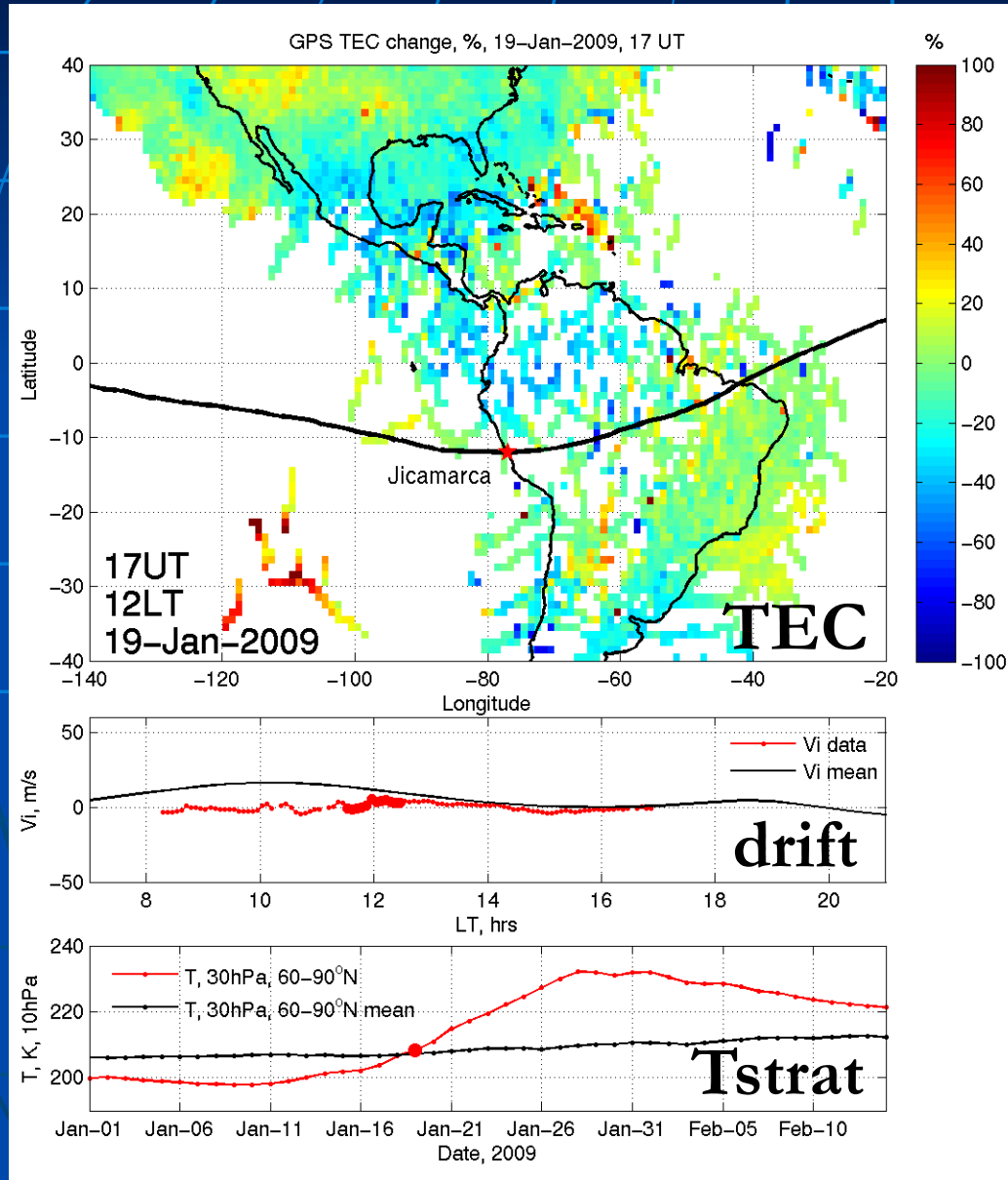
Stratospheric Zonal wind
at 60°N

Solar activity
Minimum: F10.7 < 80

Magnetic activity

Quiet: Kp < 3

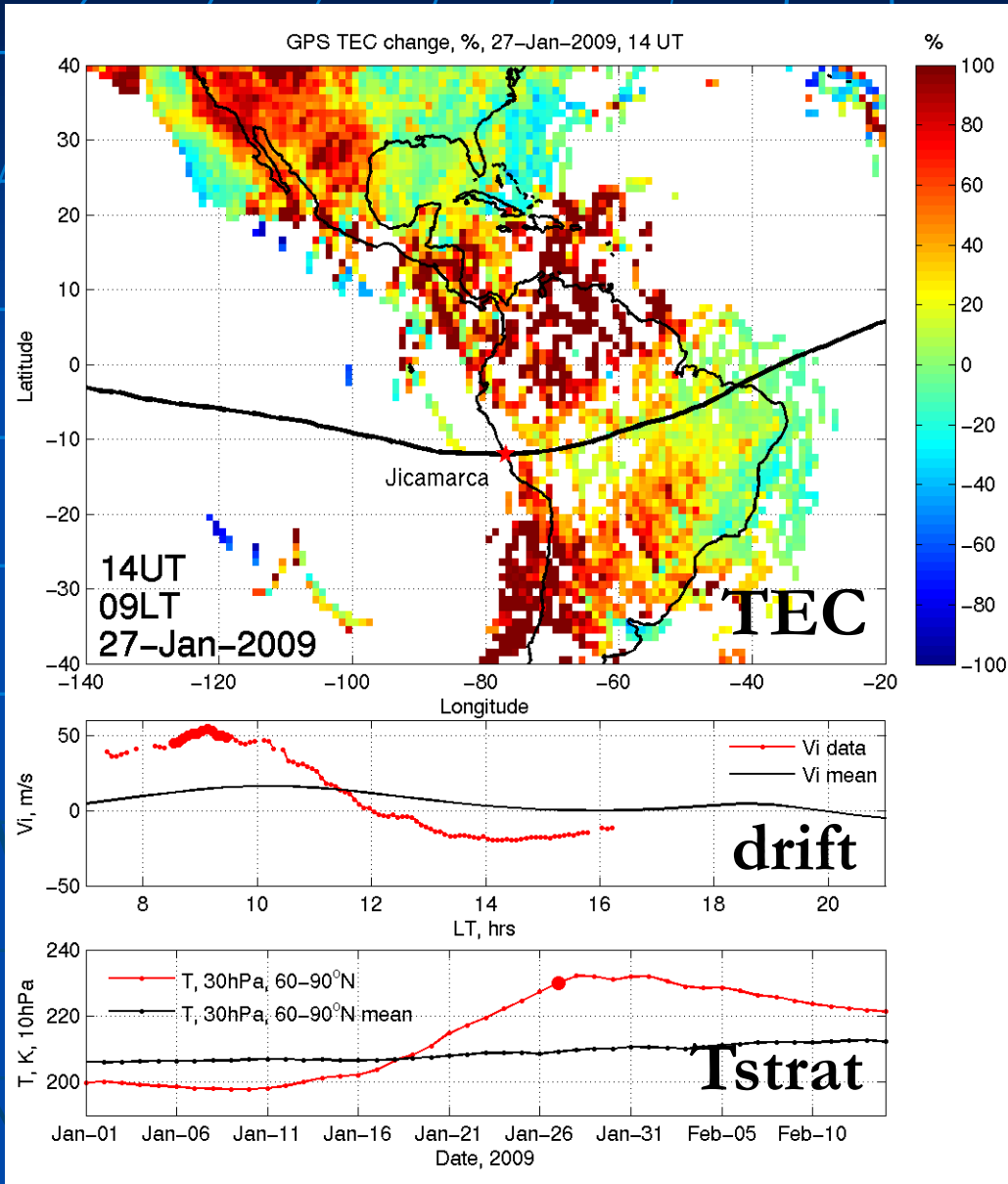
GPS TEC change – no warming



- 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

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

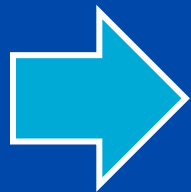


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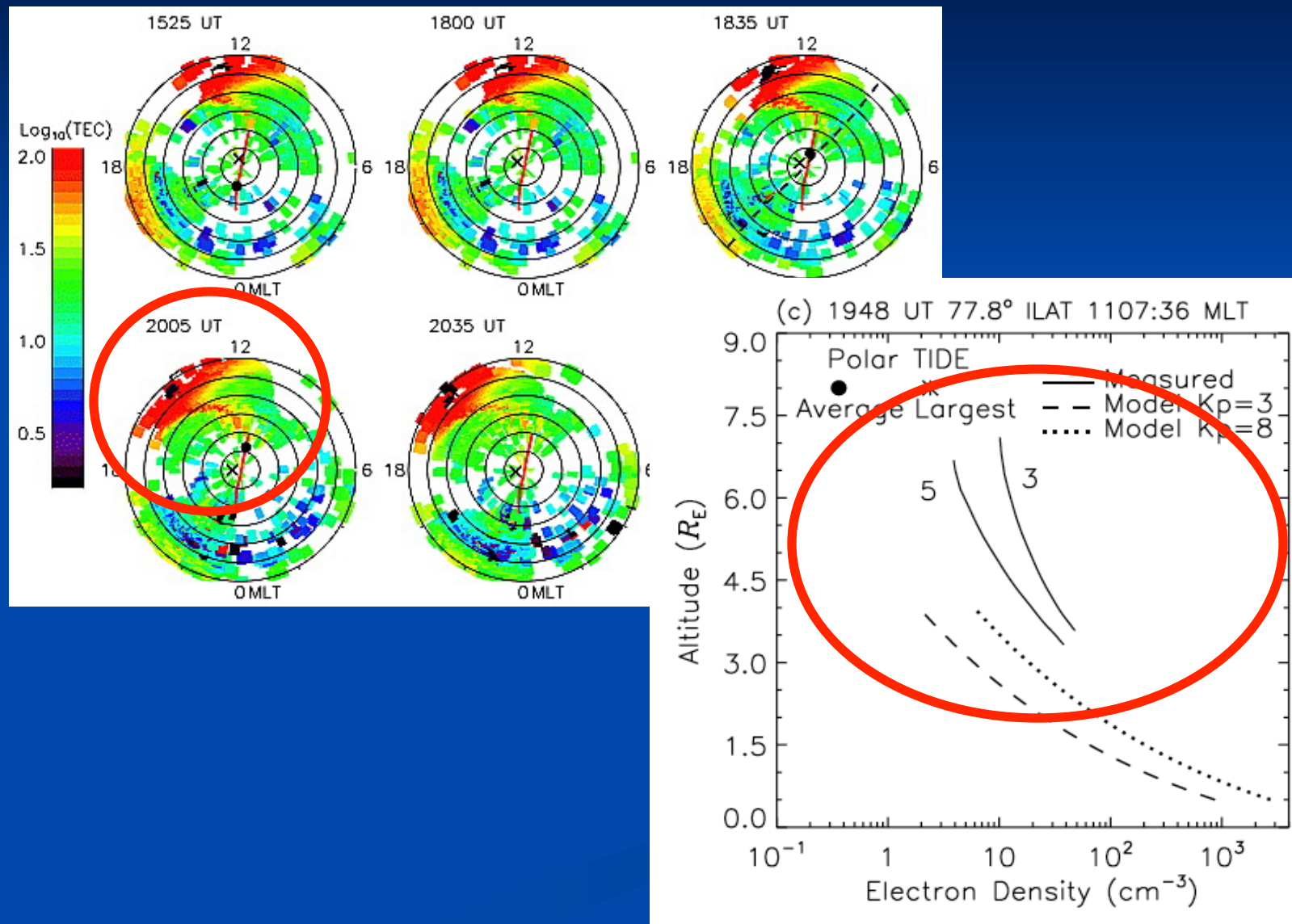
IT Coupling – GPS



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



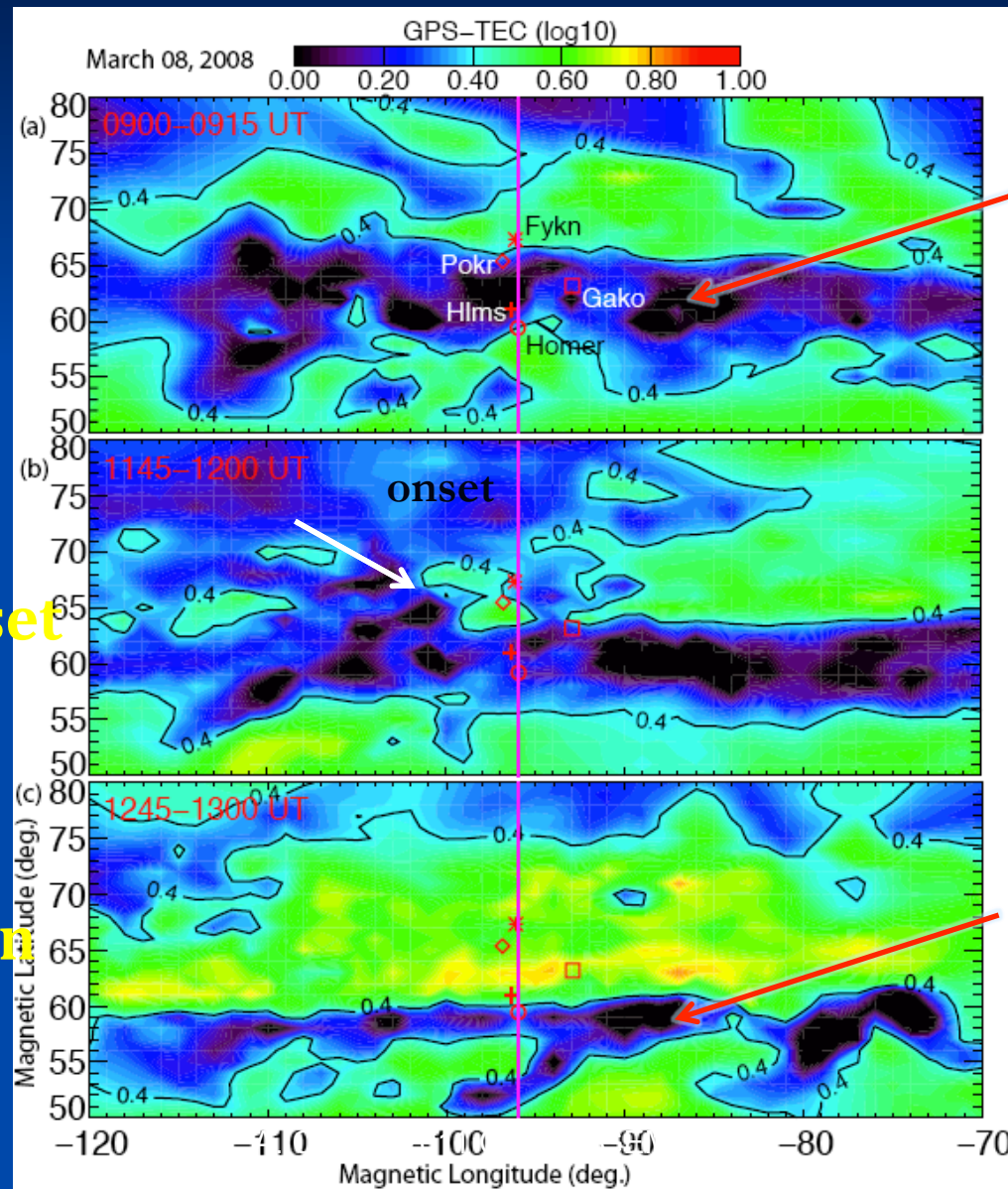
2D GPS VTEC Contour over Alaska: 2008/03/08

~11:40 UT Event Zou, S., et al., 2011, GRL

Before
onset

Right after onset

Late expansion
phase



mid-latitude
trough

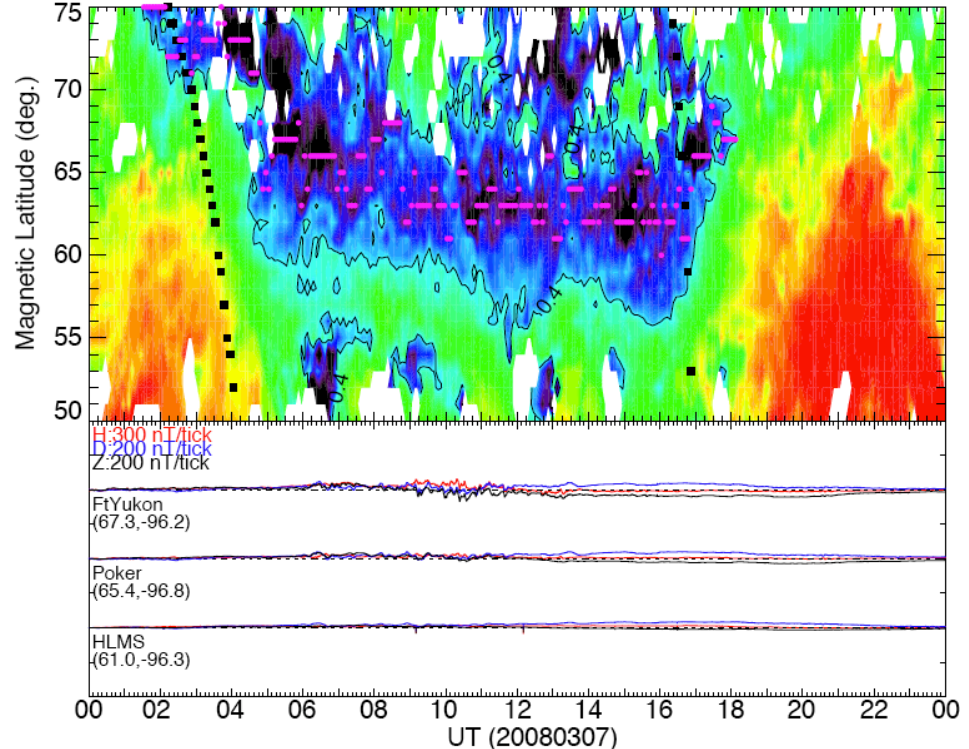
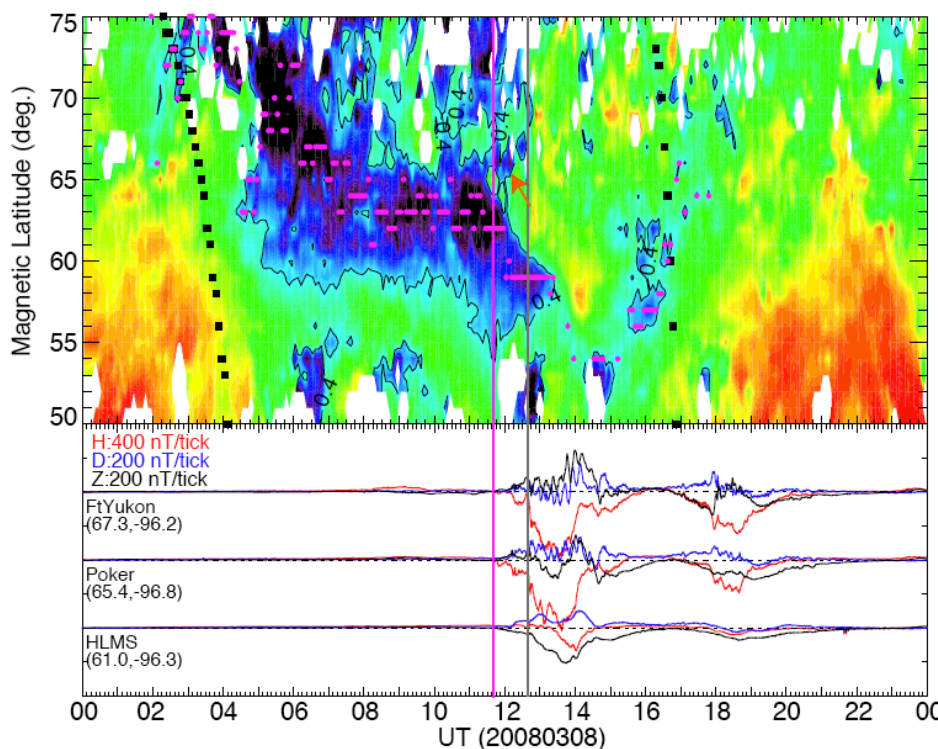
Narrowing of
mid-latitude
trough

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



2011
Aleutian
Islands,
AK

2012
Azore Islands,
Portugal

OSU – 2010
OMD, OR

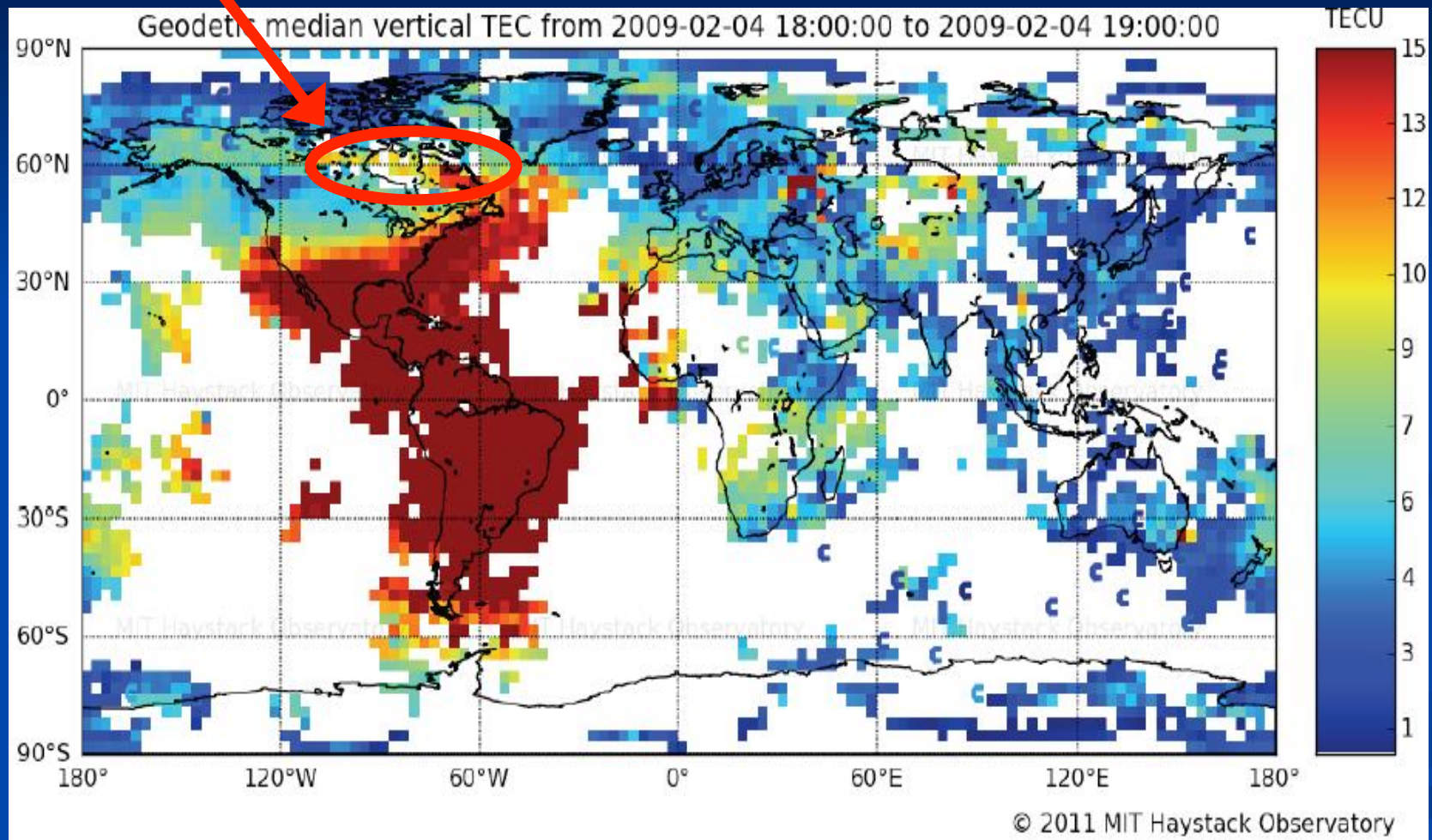
FHSU – 2009

A. Coster, 2011 CEDAR/GEM tutorial

Hays, KS



A storm enhanced density (SED)

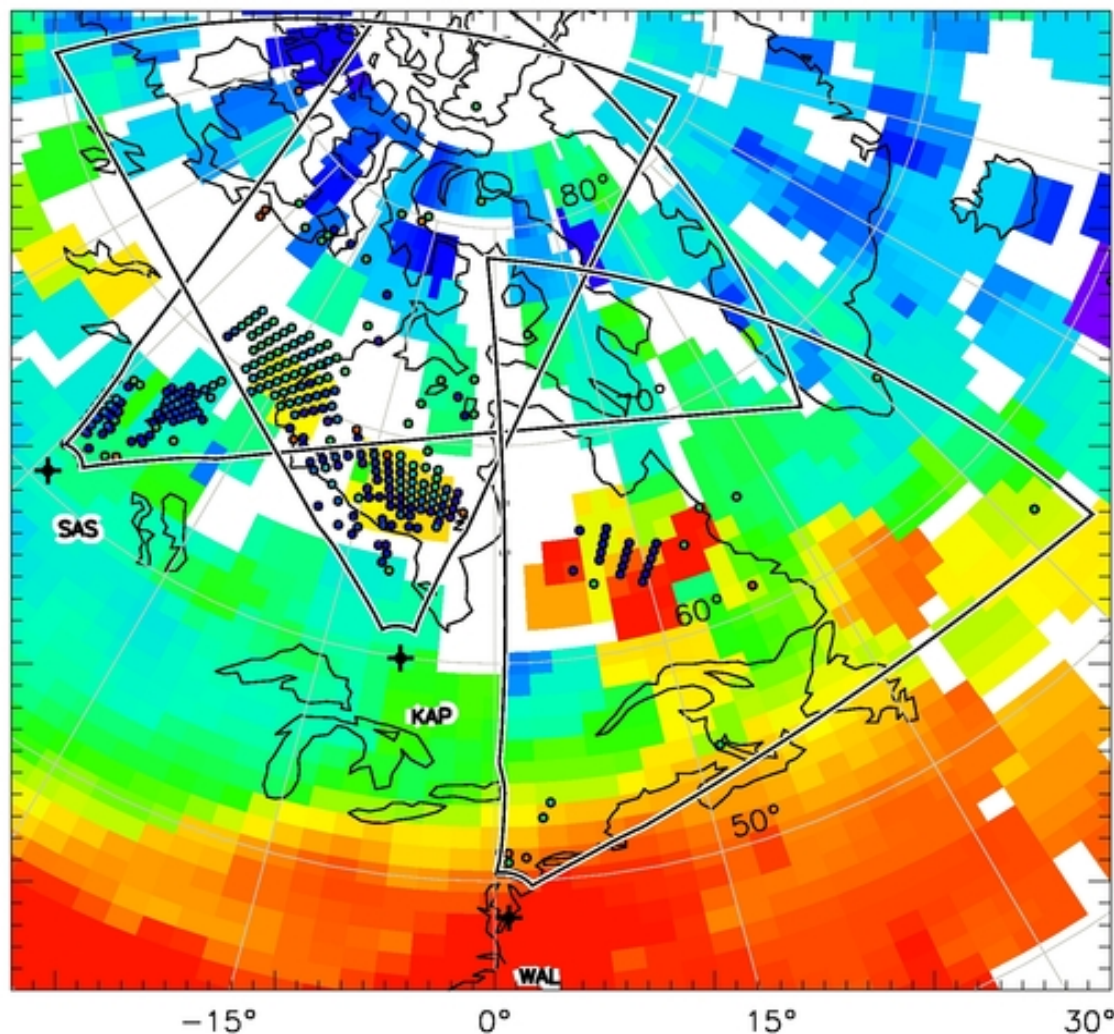


TOTAL ELECTRON CONTENT

Median Filtered, Threshold = 0.01

04/Feb/2009 18:50:00

to
04/Feb/2009 18:55:00.0



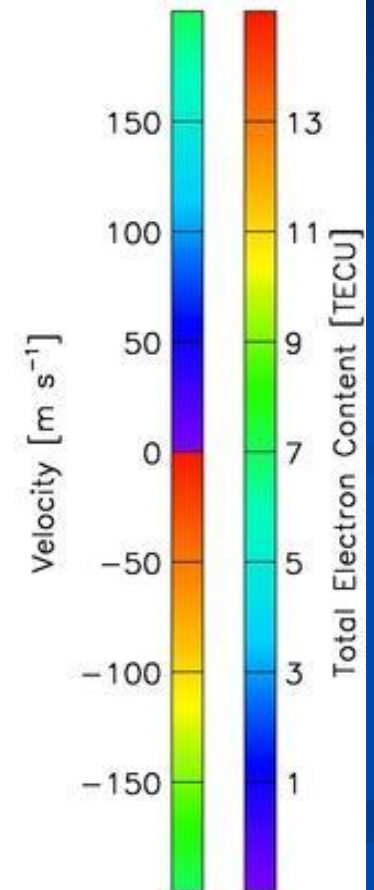
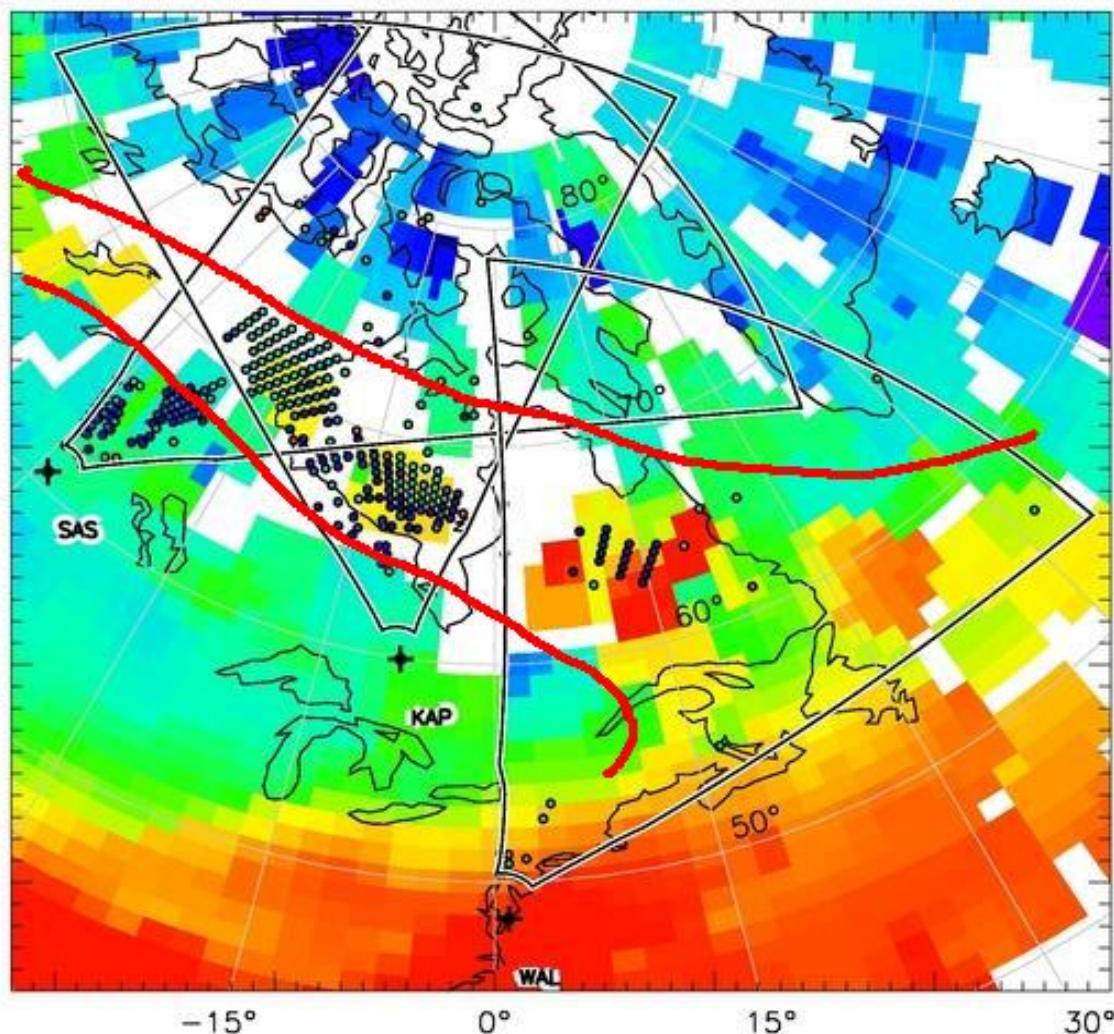
TOTAL ELECTRON CONTENT

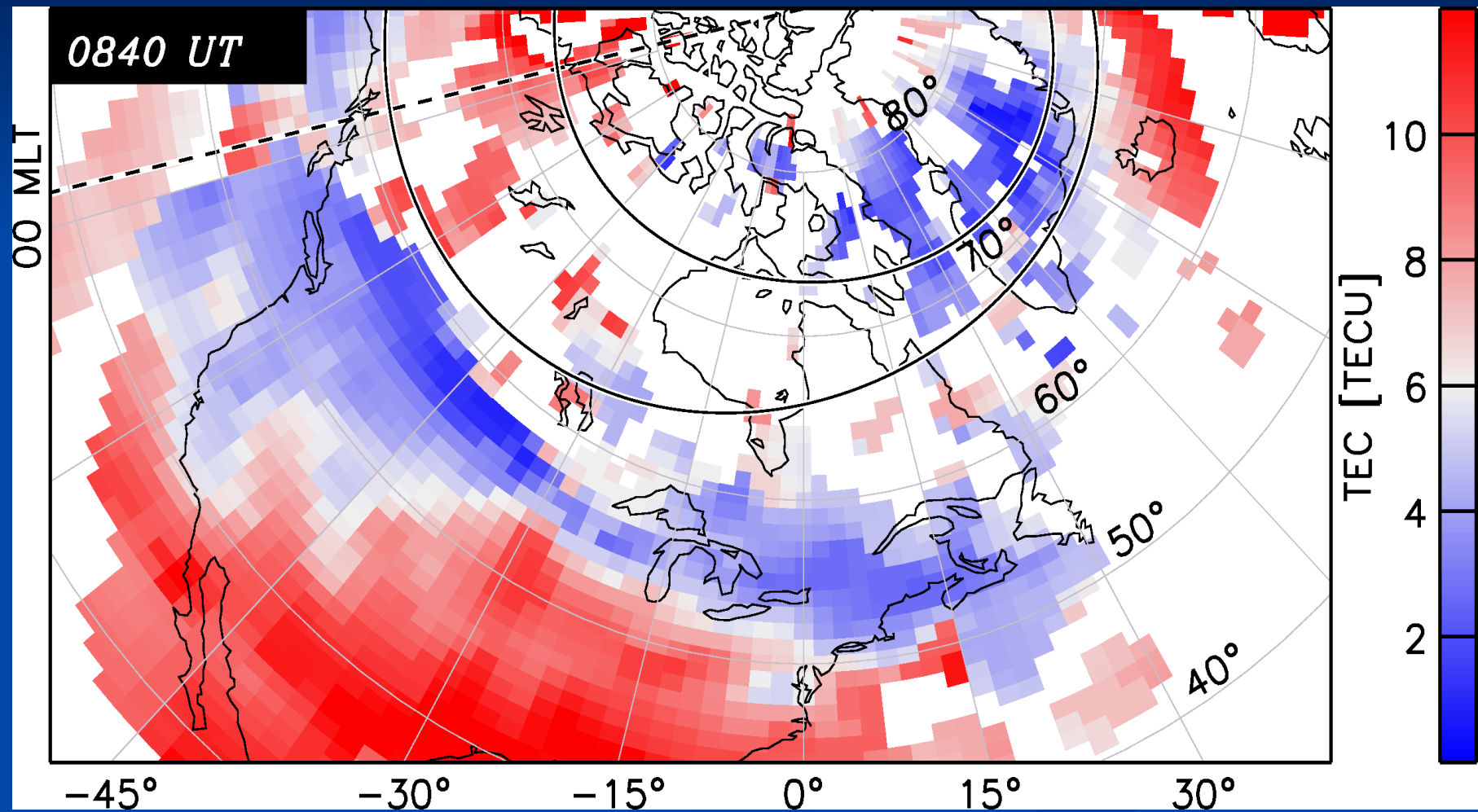
Median Filtered, Threshold = 0.01

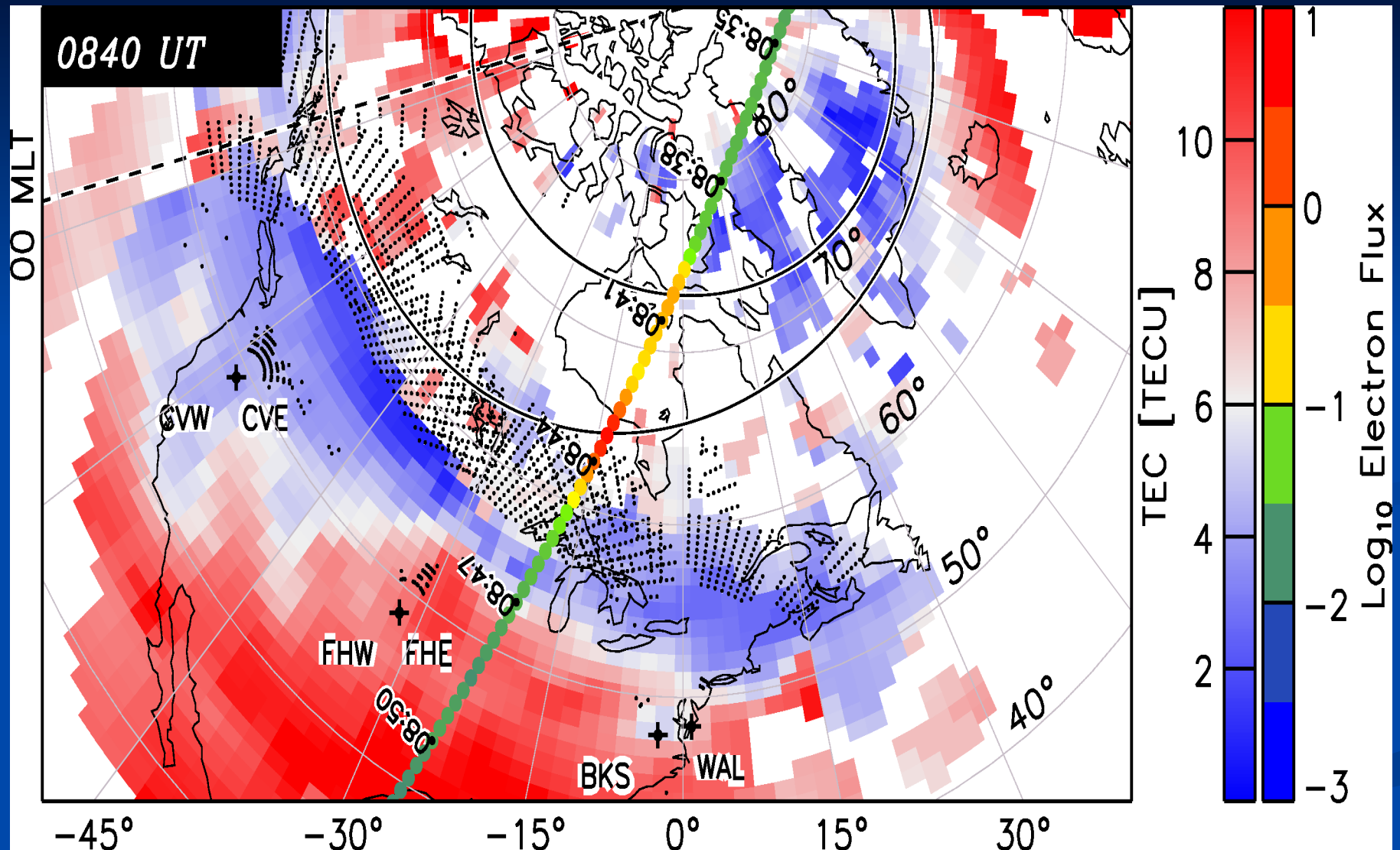
04/Feb/2009 18:50:00

to

04/Feb/2009 18:55:00.0







Ionospheric Tomography with GPS

Yizengaw, et al., 2006b

courtesy of C. Mitchell

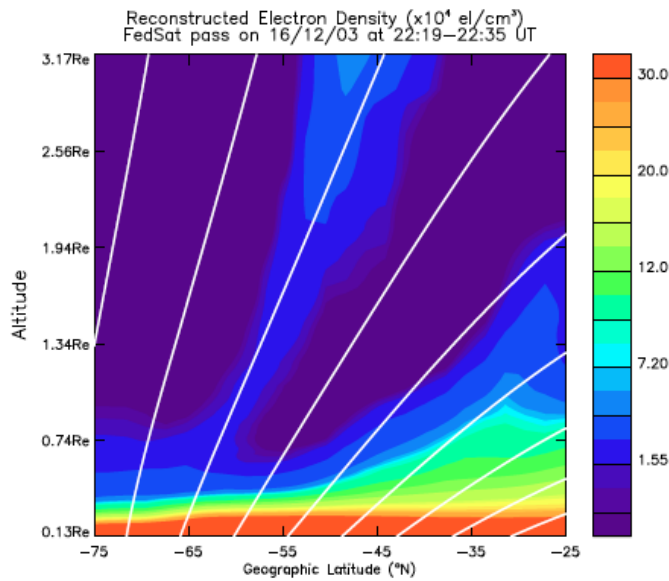
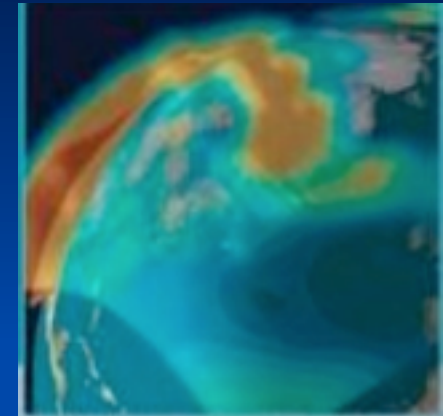
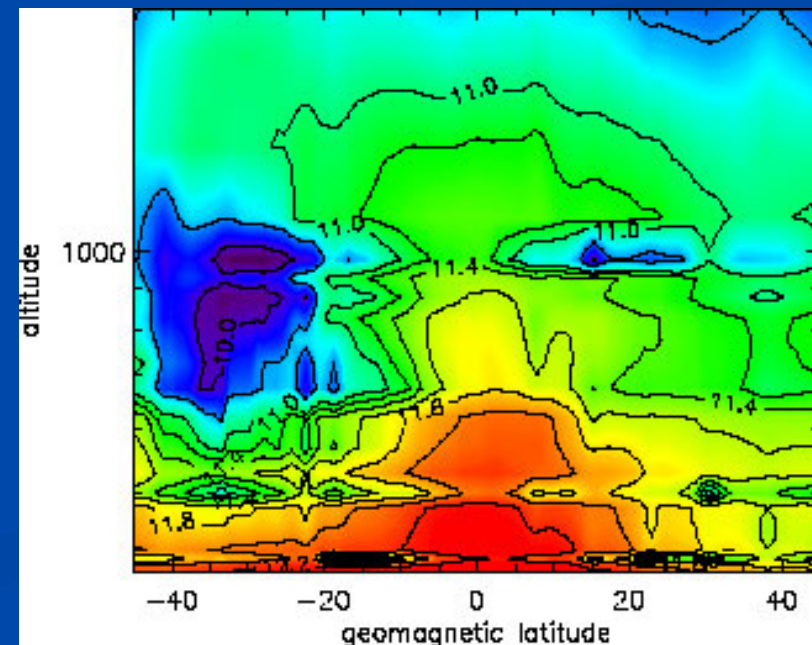


Figure 5. Tomographically reconstructed density distribution using data recorded by GPS receiver on FedSat. The curved white lines depict the magnetic field lines obtained from Tsyganenko 01-model (after Yizengaw et al., 2006b).

Courtesy of G. Bust



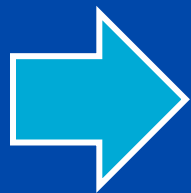
Outline

ABC's of GPS

Some history of measuring the
ionosphere with GPS

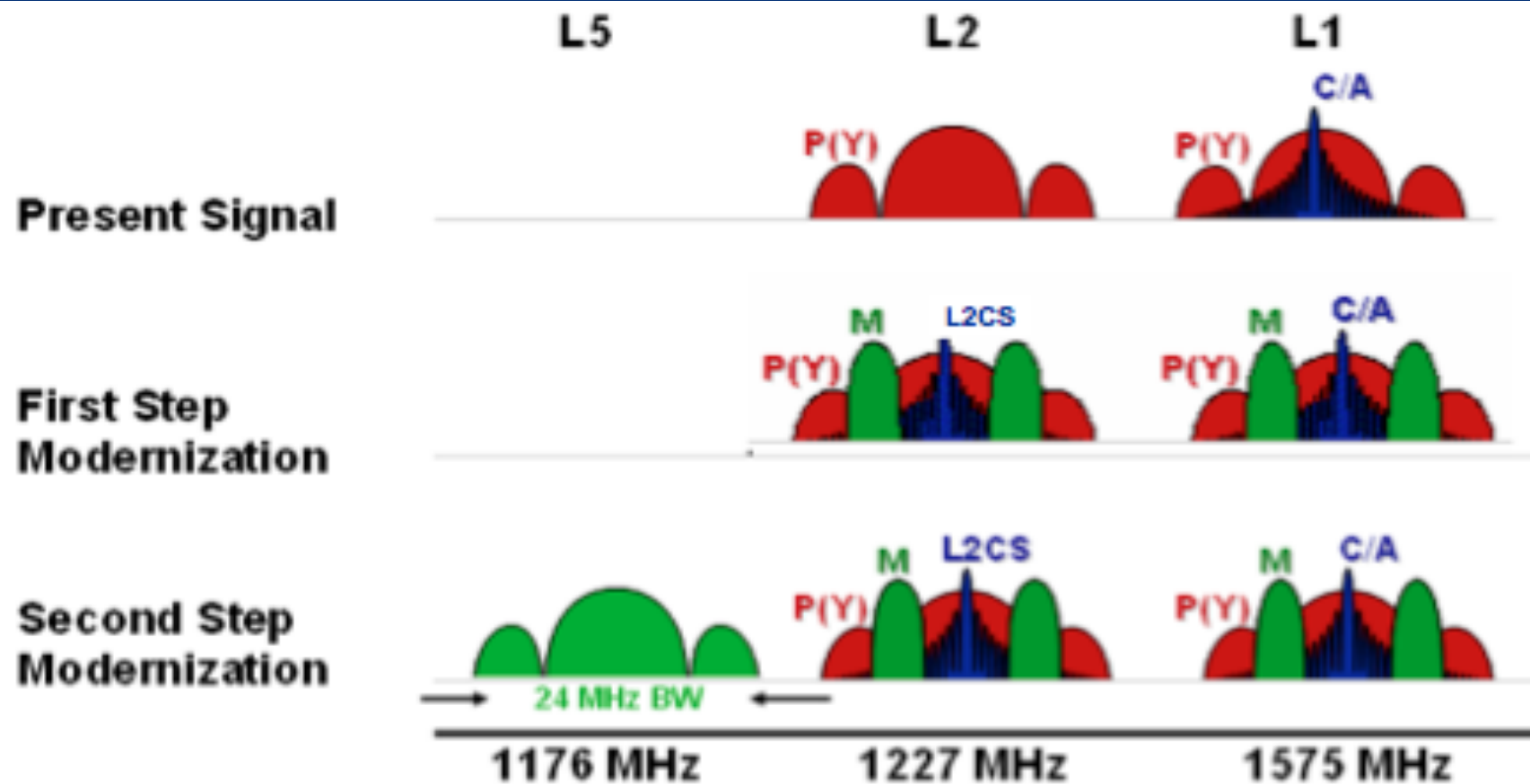
IT Coupling – GPS

MI Coupling – GPS



What's on the horizon

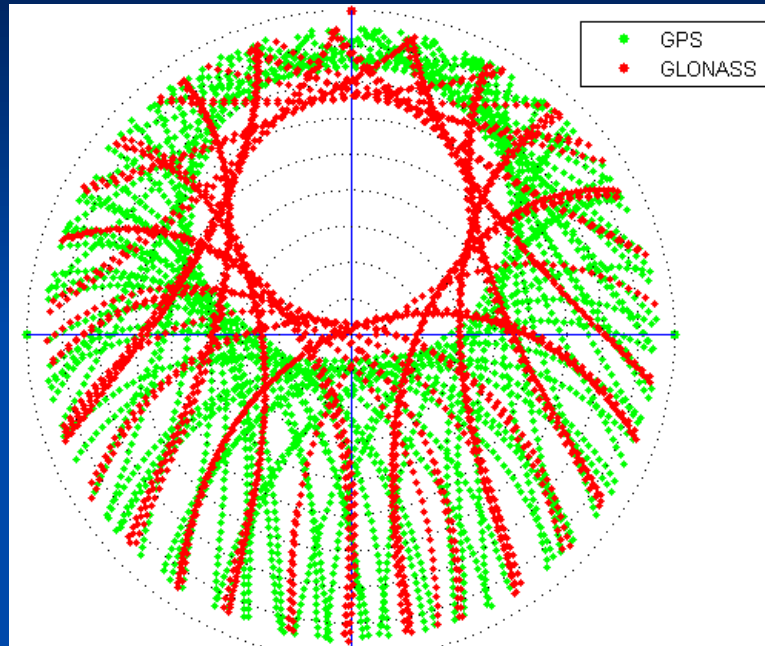
GPS Modernization



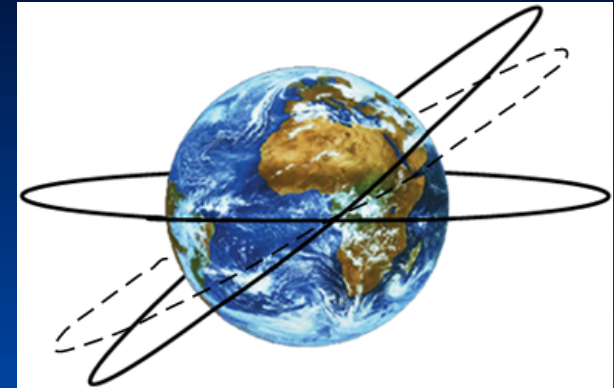
1

ALL ORIGINAL SIGNALS WILL REMAIN THE SAME

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



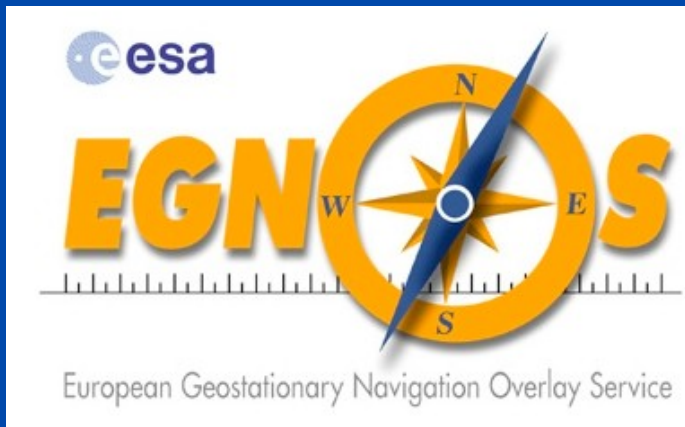
GLONASS orbit plane inclination: 65°



COMPASS



GALILEO

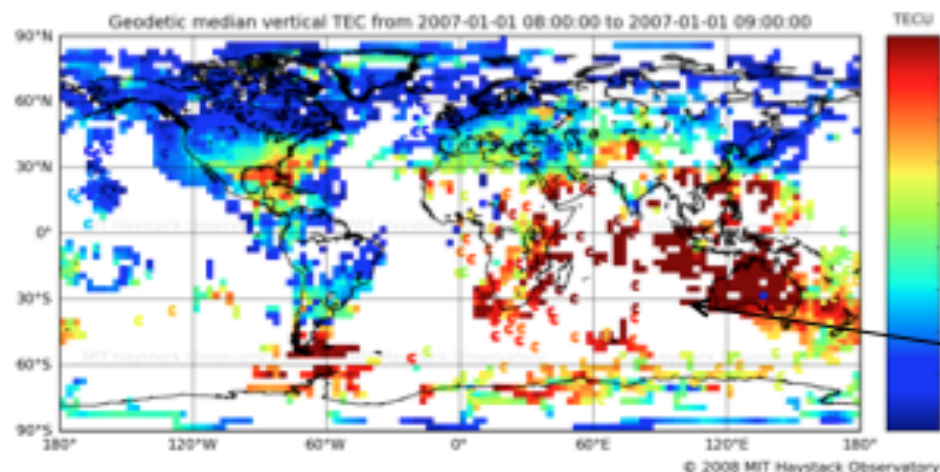




HAYSTACK OBSERVATORY

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:

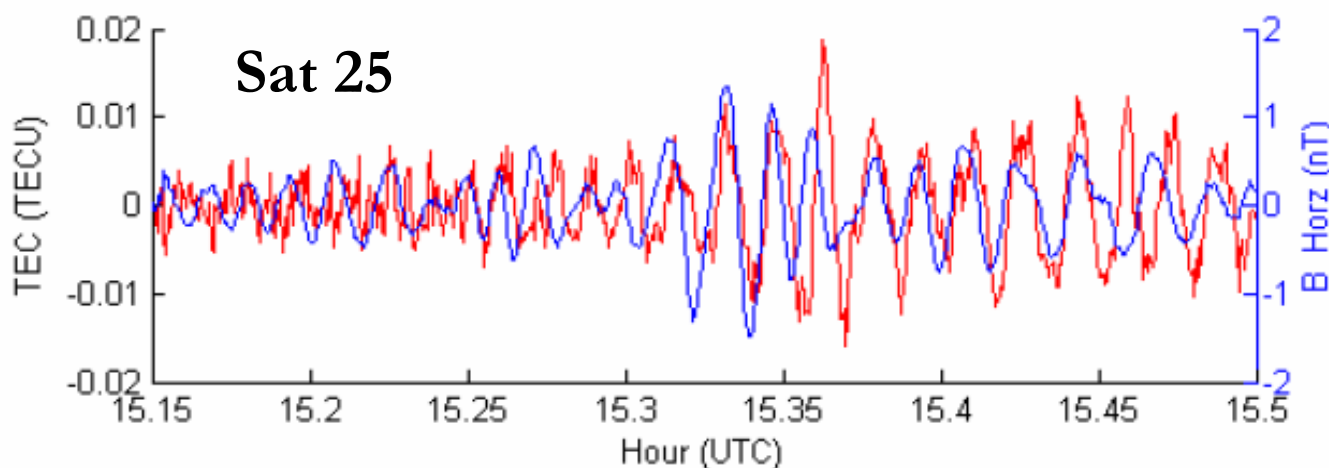
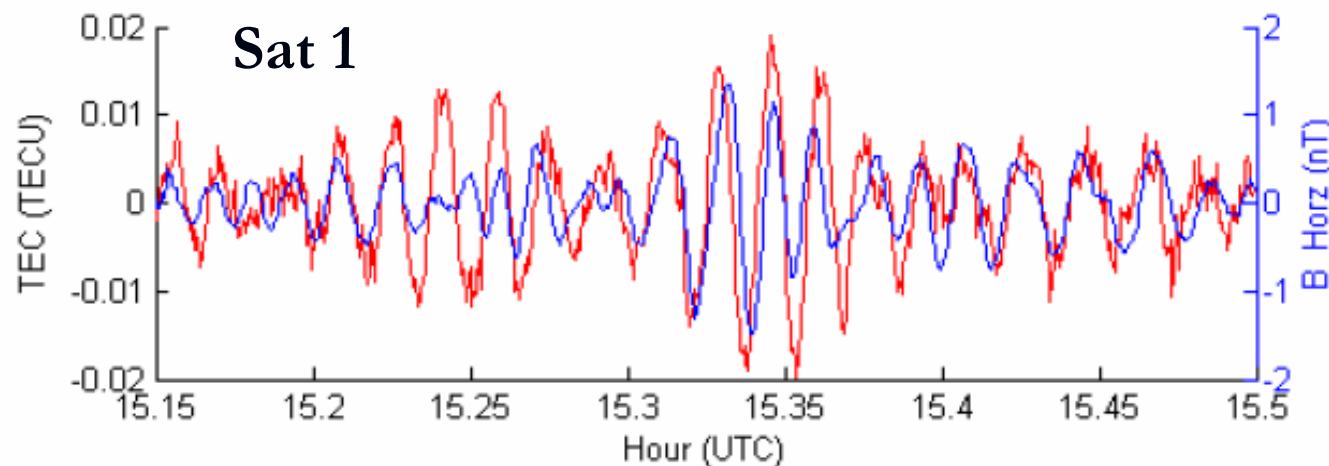
1. Cost
2. Power
3. Lack of civilian signal on second frequency

White areas indicate no data

Why Now ?

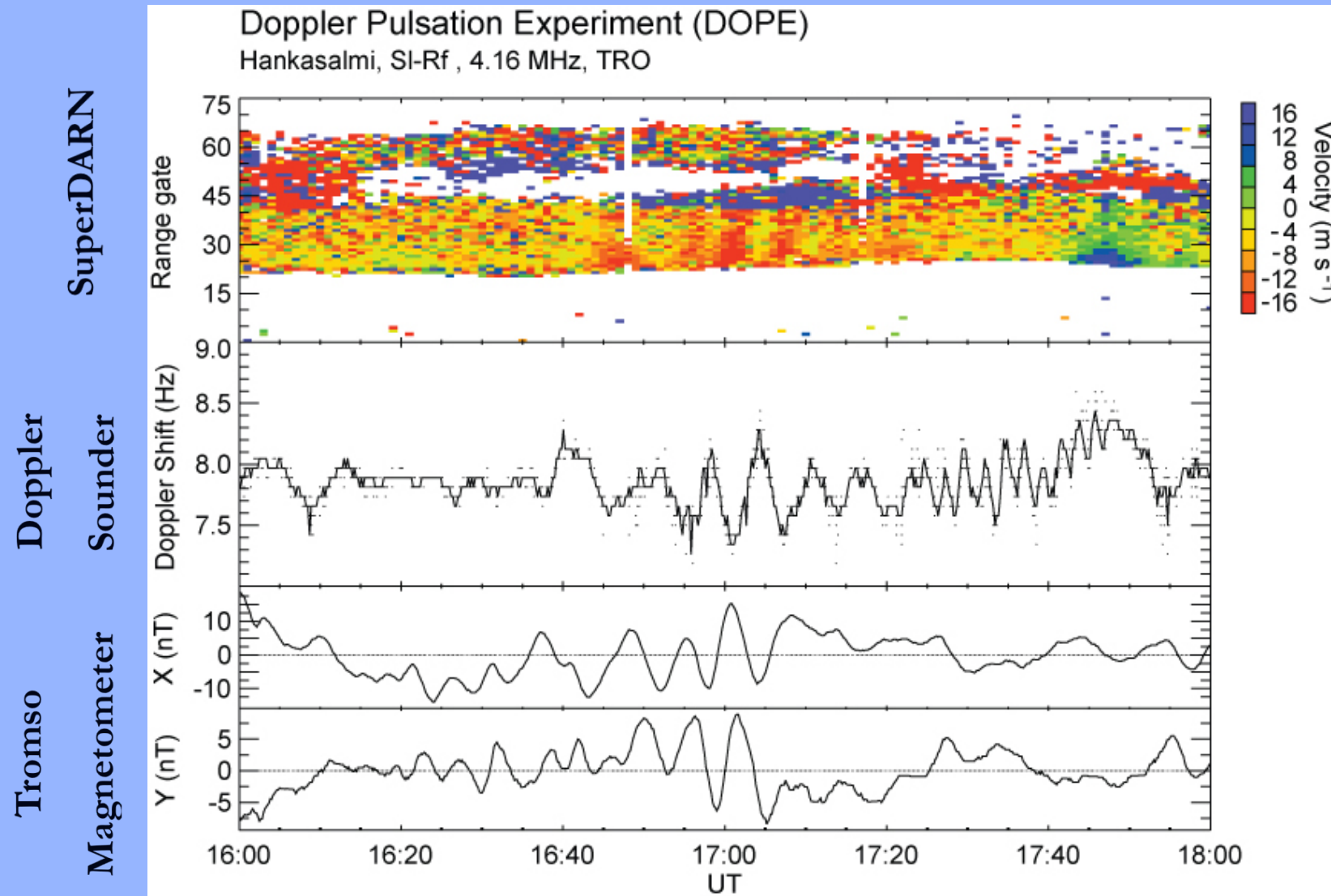
- Modernized GPS offers new civilian signals on two new frequencies
- New software receivers use less power and substantially reduce cost (factor of ~5)

Correlation of magnetometer measurements with GPS TEC

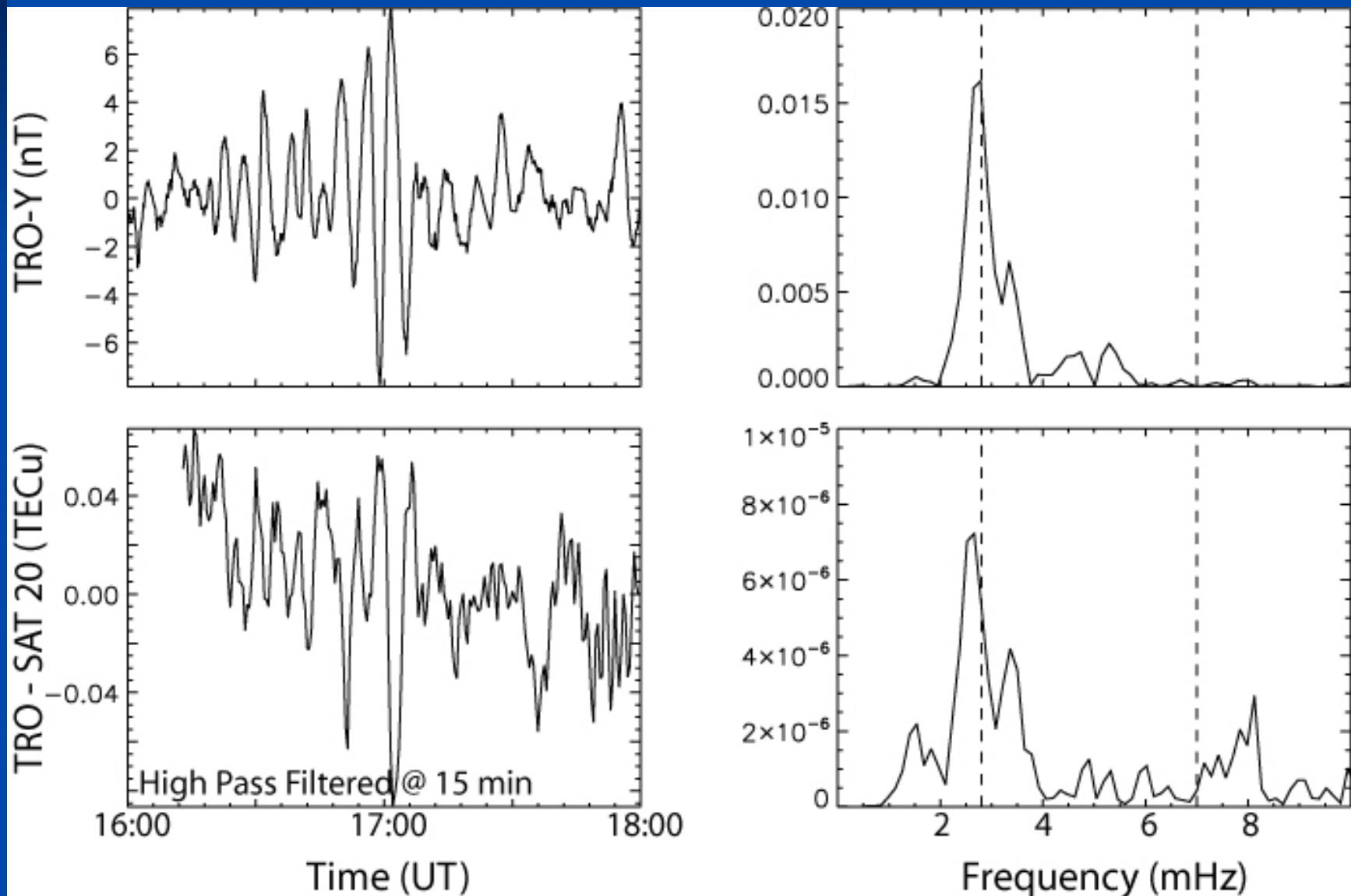


Example of small-scale pulsations not observed on the ground

courtesy of D. Murr



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.