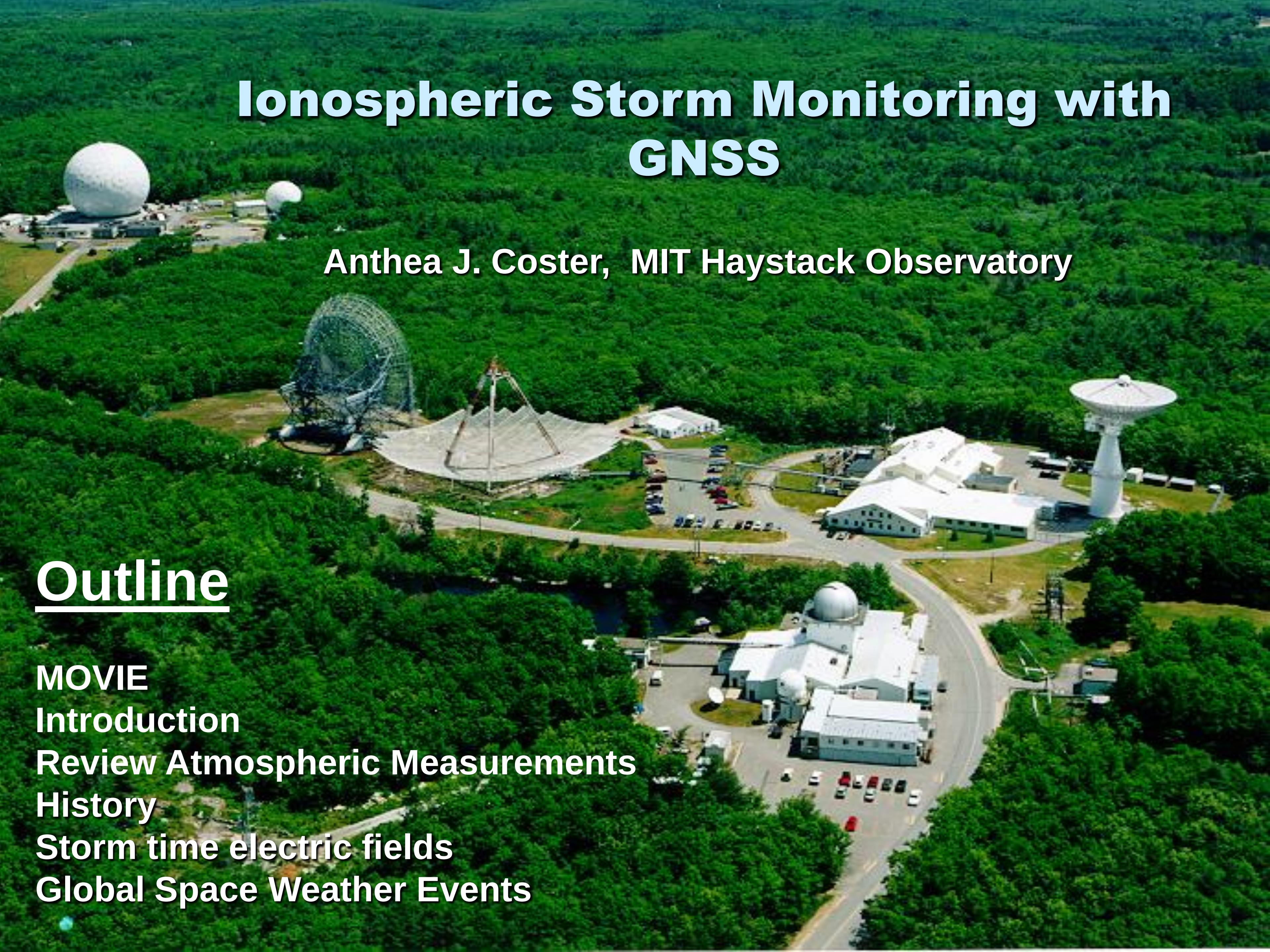


Ionospheric Storm Monitoring with GNSS

Anthea J. Coster, MIT Haystack Observatory

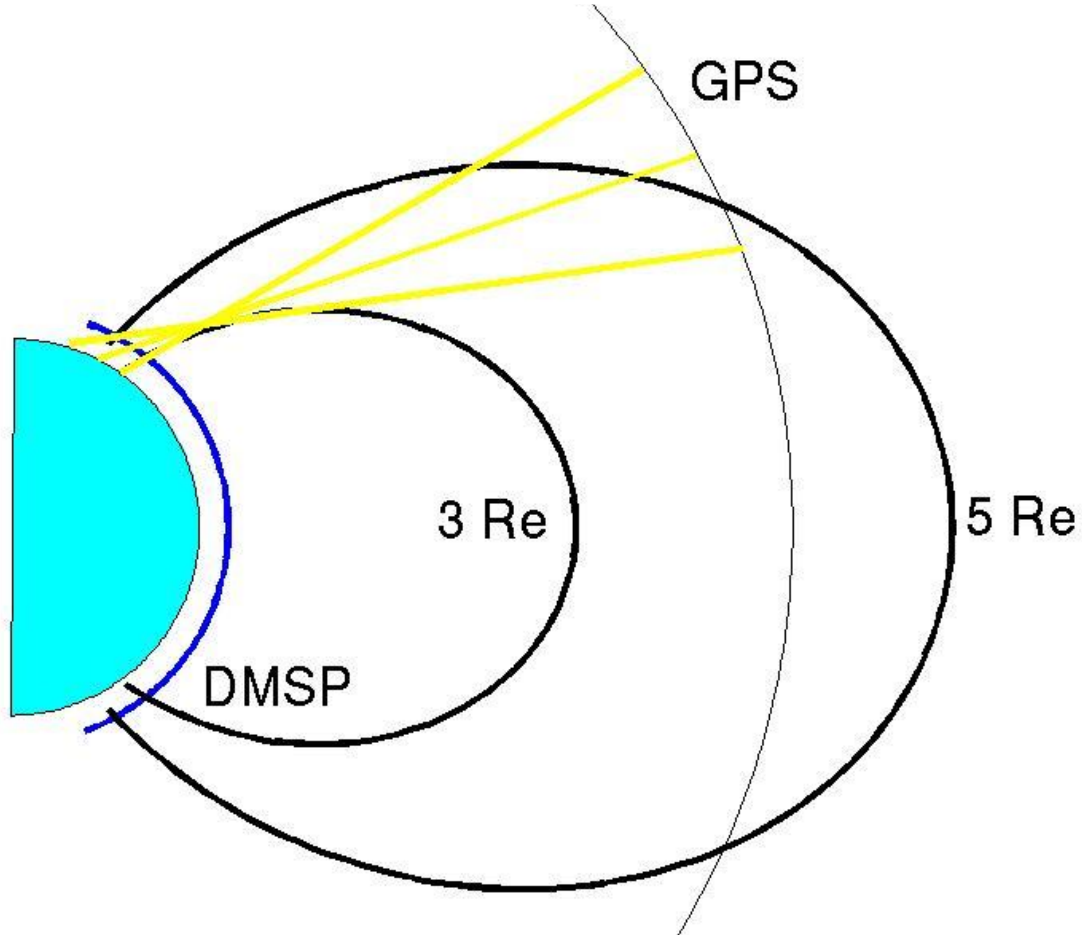
Outline

MOVIE
Introduction
Review Atmospheric Measurements
History
Storm time electric fields
Global Space Weather Events

Definition:

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

GPS samples the ionosphere and plasmasphere to an altitude of ~20,000 km

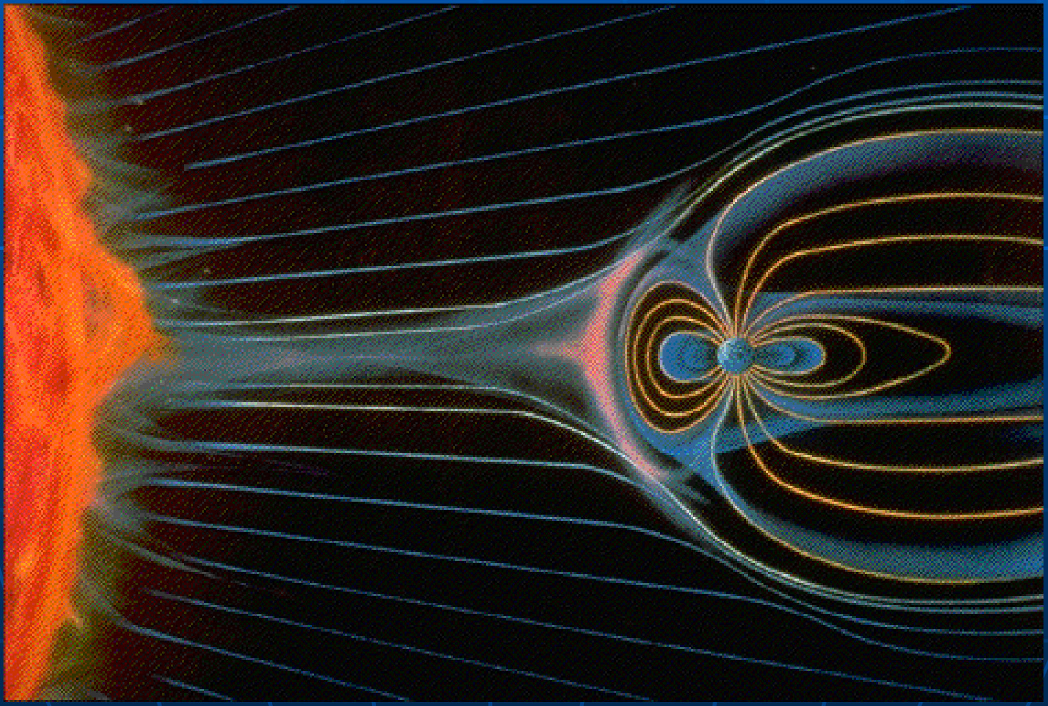


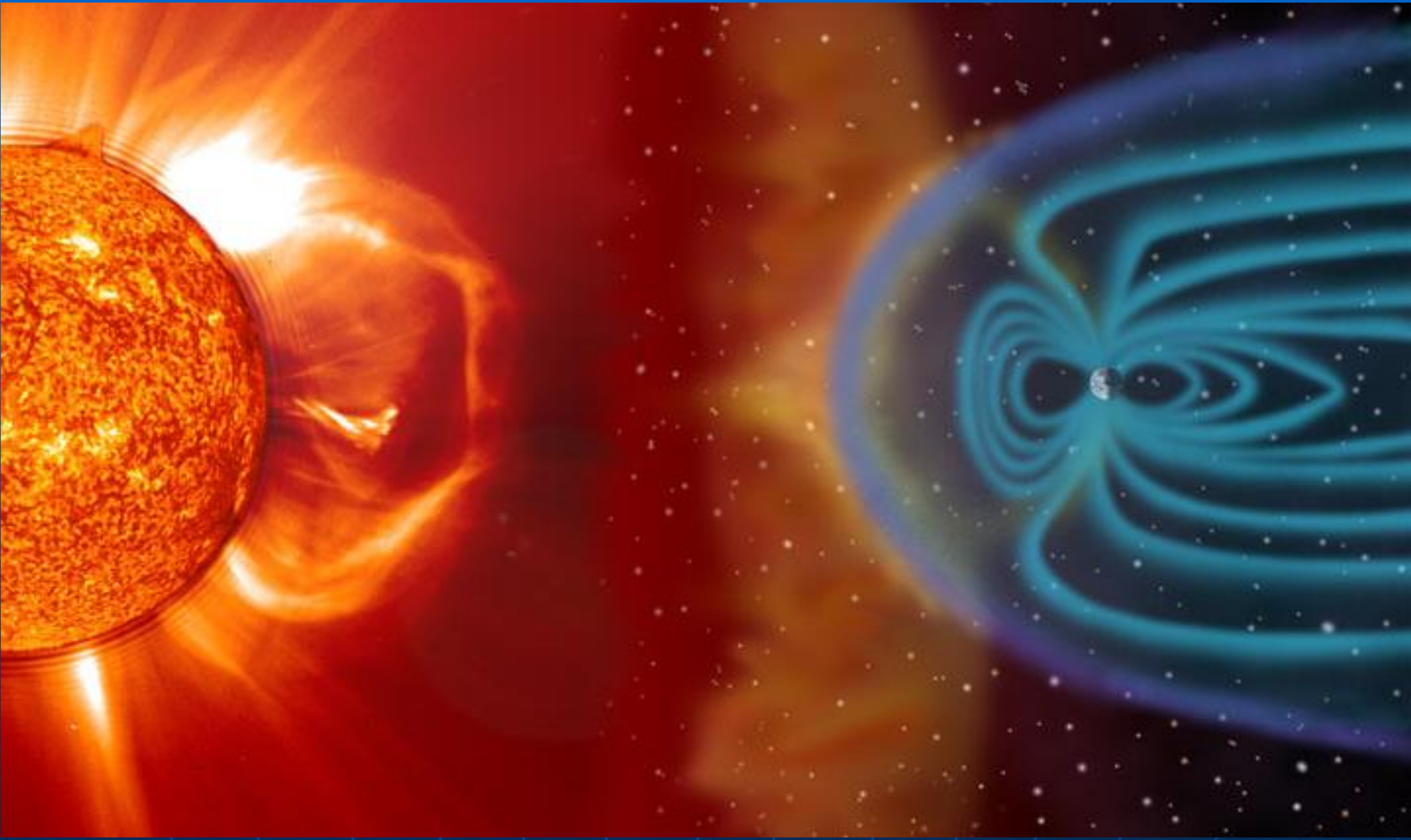
TEC is a measure of integrated density in a 1 m^2 column

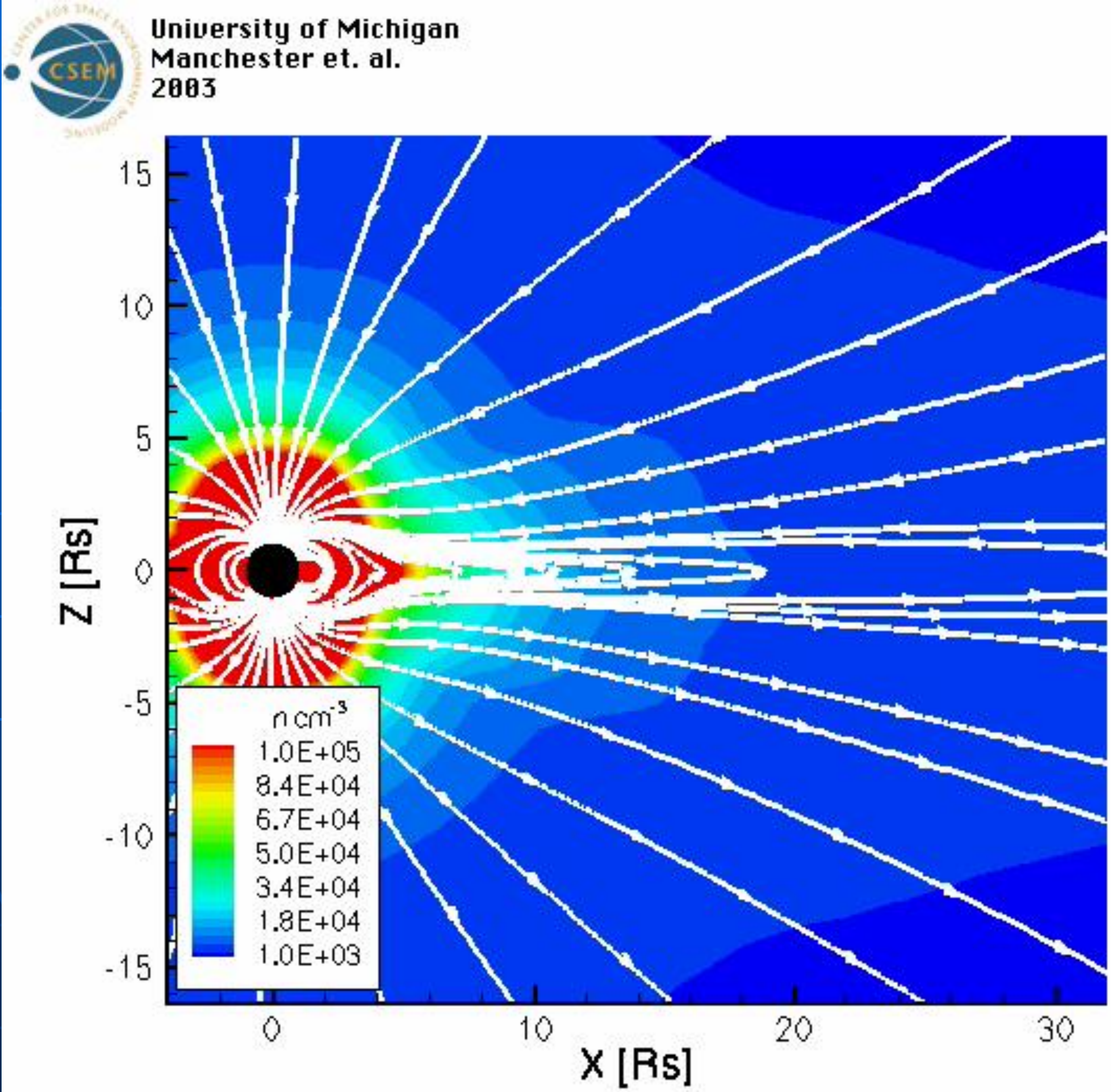
1 TEC unit = 10^{16} electrons m^{-2}

Space Weather

- **Definition:**
  - ***"Conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can affect performance and reliability of space-based and ground-based technological systems."****



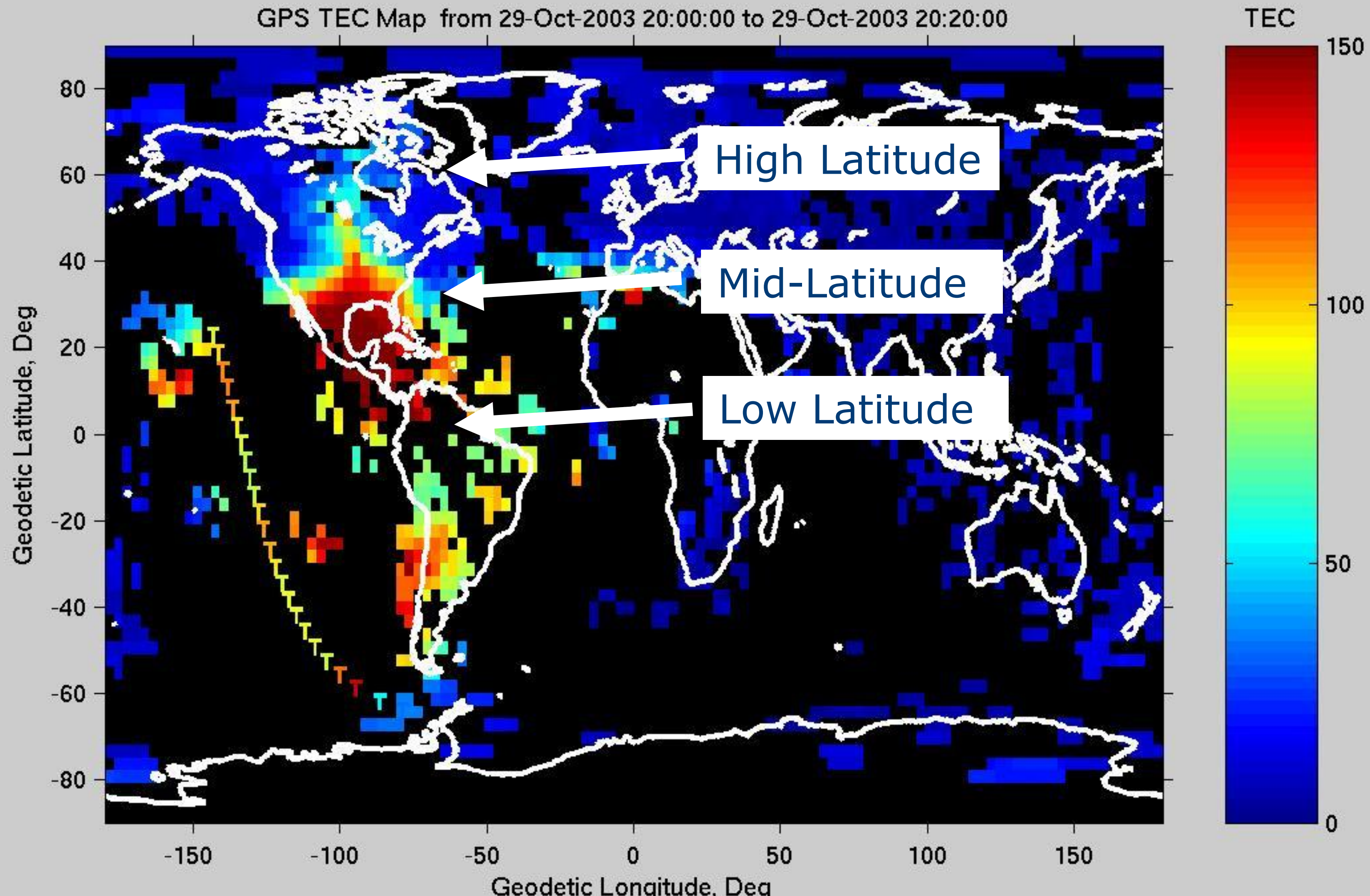



University of Michigan
Manchester et. al.
2003
CSEM
Z [Rs]
X [Rs]
n cm-3
1.0E+05
8.4E+04
6.7E+04
5.0E+04
3.4E+04
1.8E+04
1.0E+03
15
10
5
0
-5
-10
-15
0
10
20
30

Northwest Territories, Canada

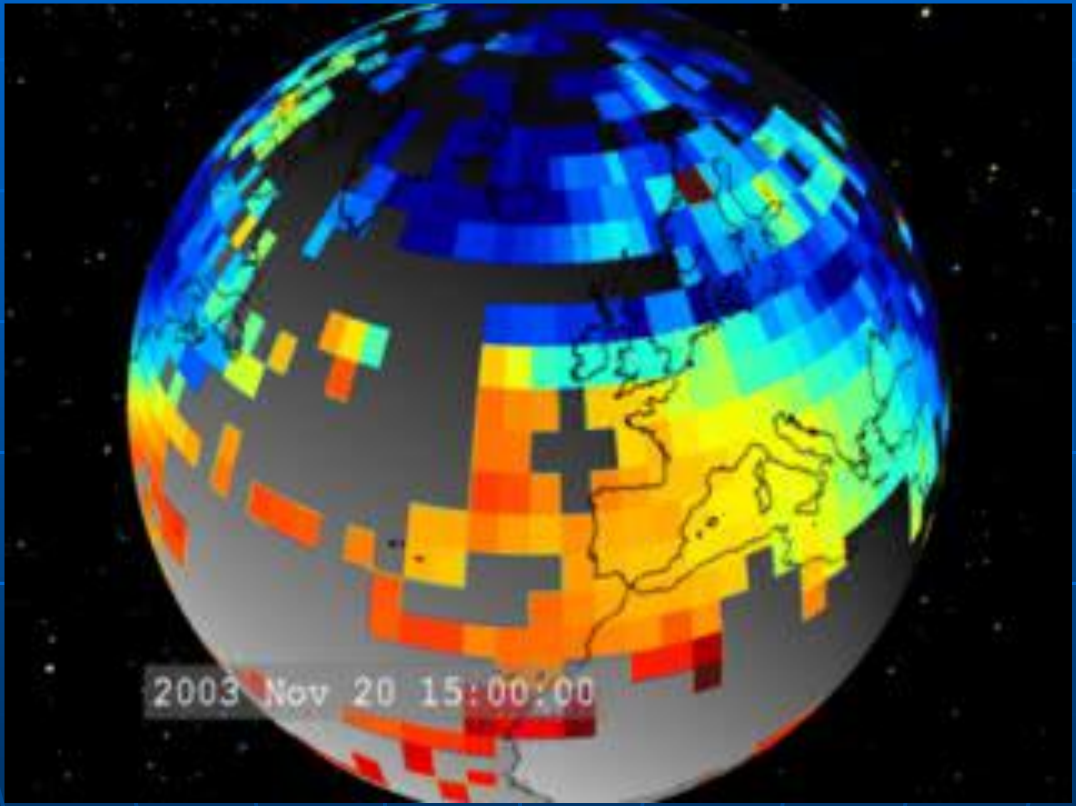
West Texas 15 Sept 2000
near El Paso Texas

(from astronomy picture of the day)



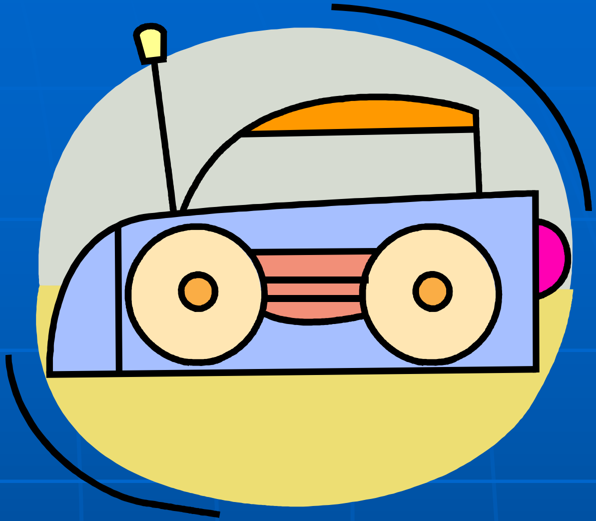
Day302
PM
MIT Haystack Observatory
GPS TEC Map from 29-Oct-2003 20:00:00 to 29-Oct-2003 20:20:00
TEC
150
100
50
0
80
60
40
20
0
-20
-40
-60
-80
Geodetic Latitude, Deg
-150
-100
-50
0
50
100
150
Geodetic Longitude, Deg
High Latitude
Mid-Latitude
Low Latitude

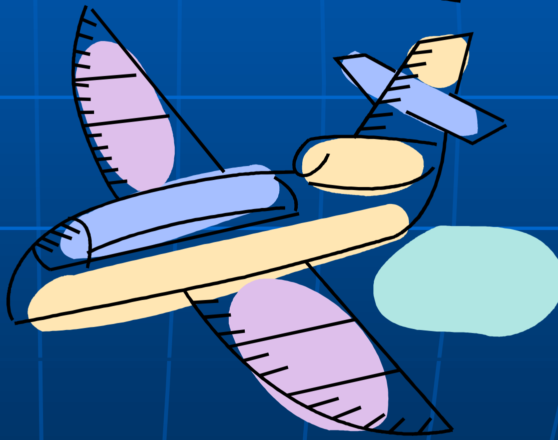
Space Weather



Why do we care?

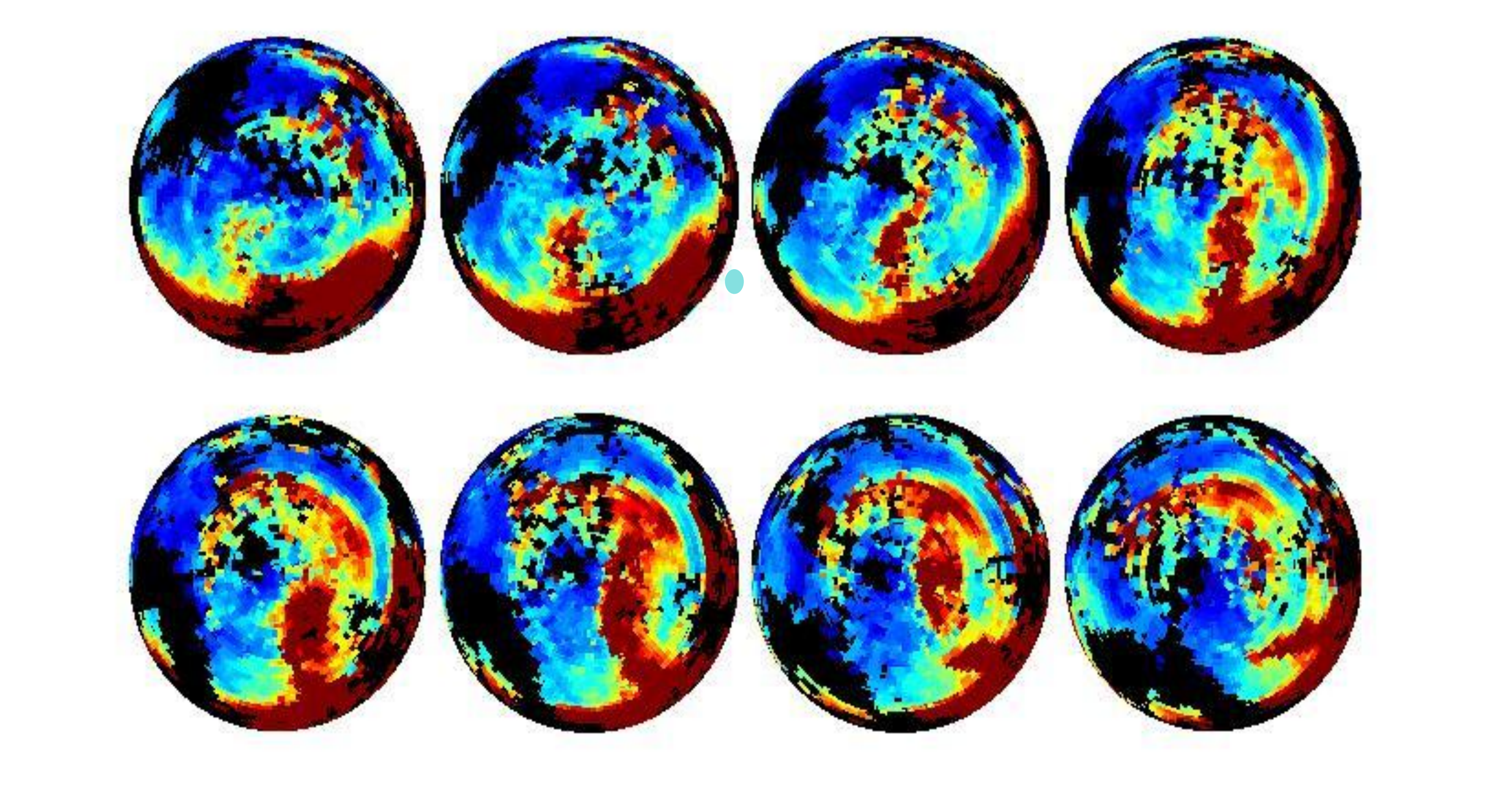




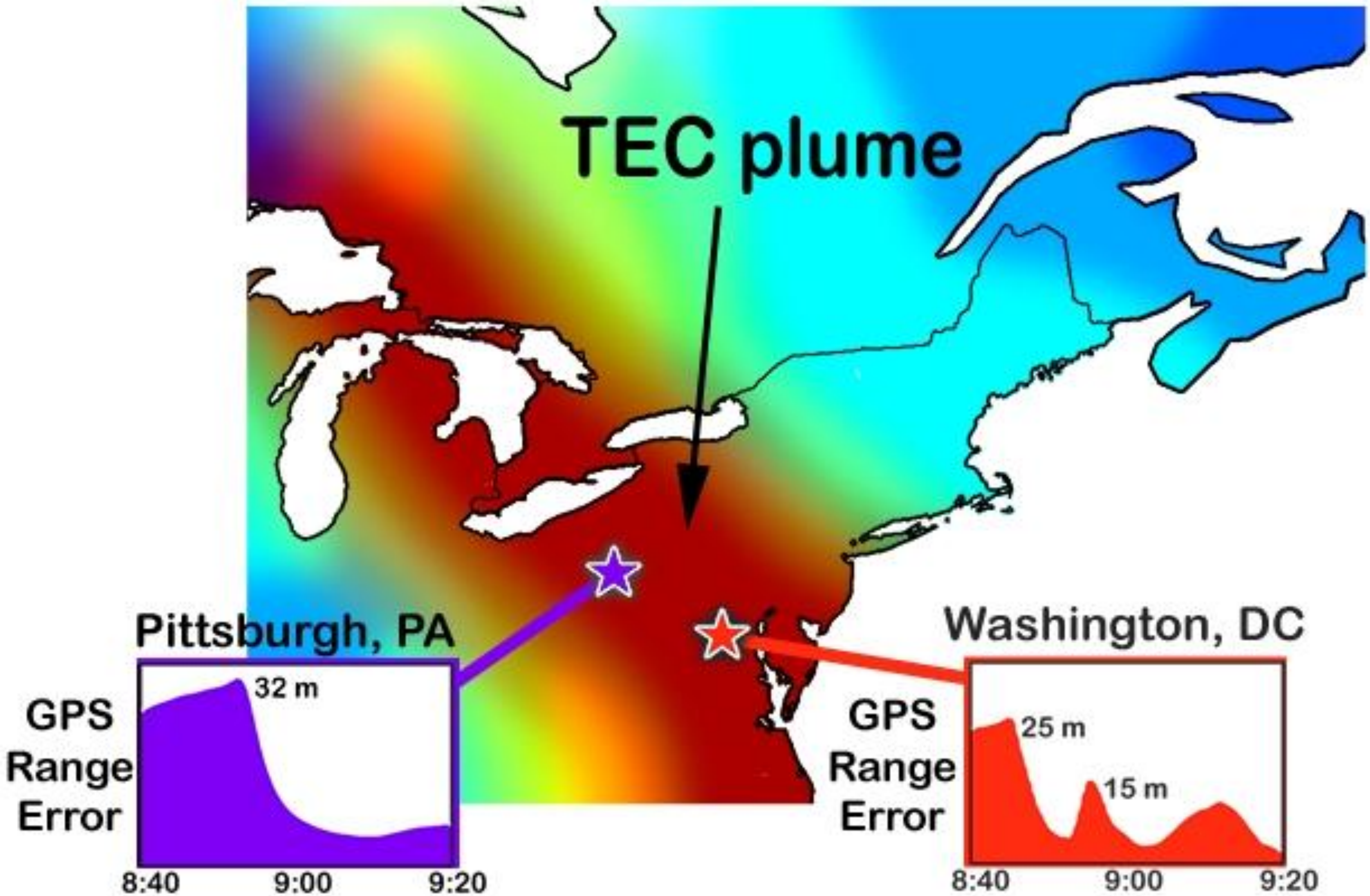




Never before has our society depended so much on radio waves that can be disrupted by the effects of the Sun's activity on the Earth.

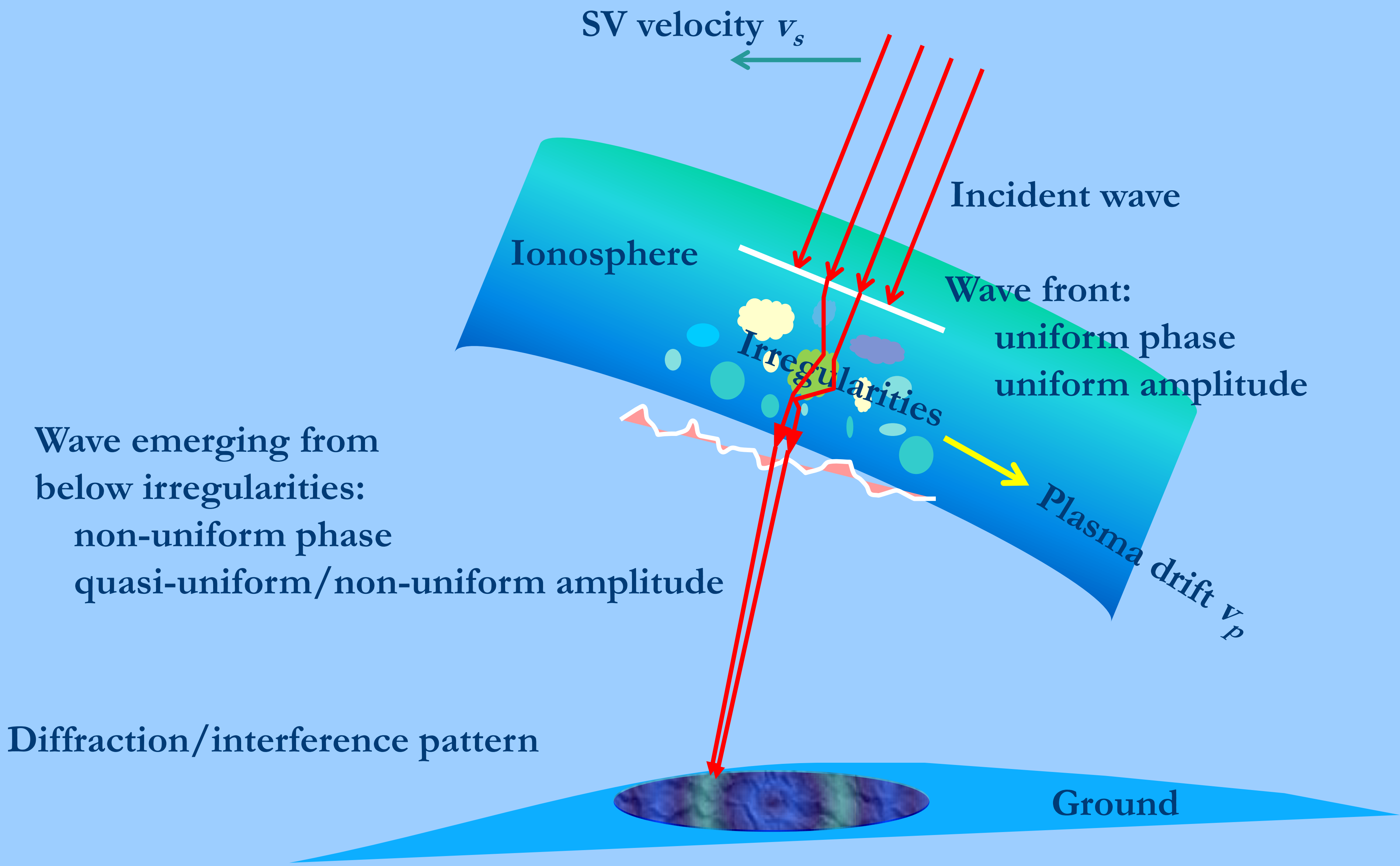
Space Weather



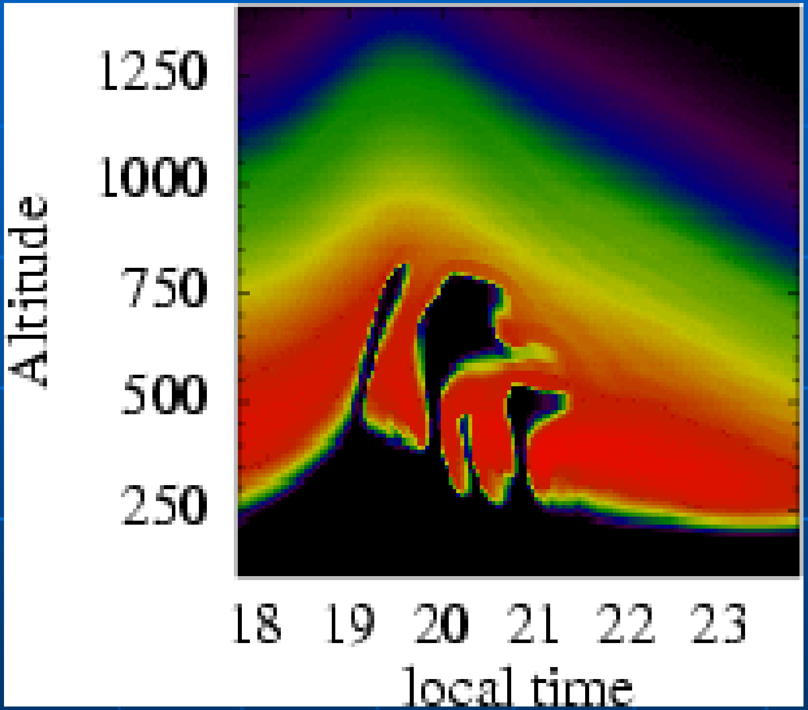
November 20, 2003

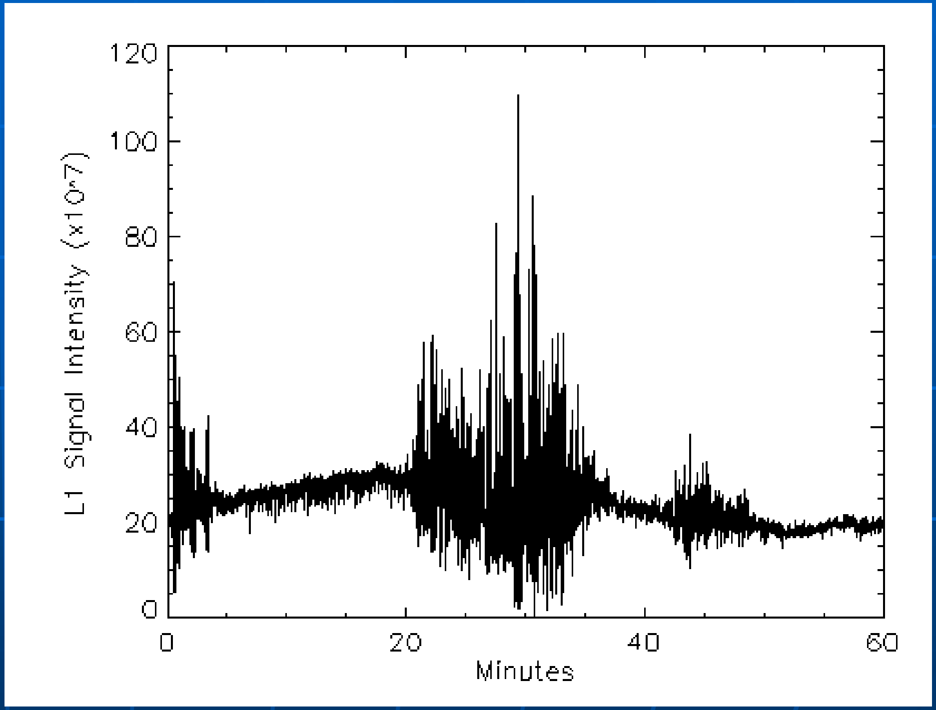


Space Weather - Scintillation



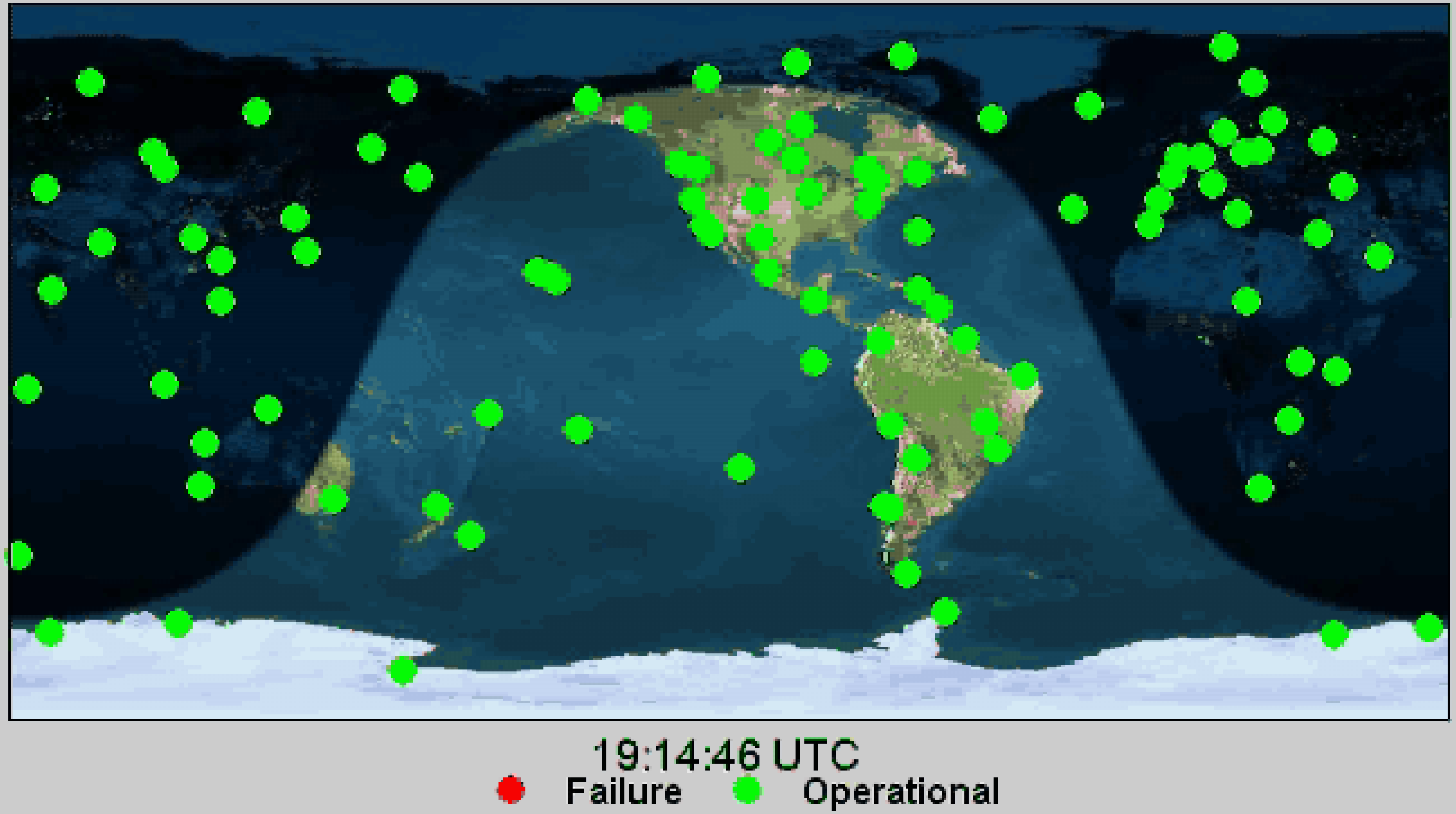
Space Weather - Scintillation

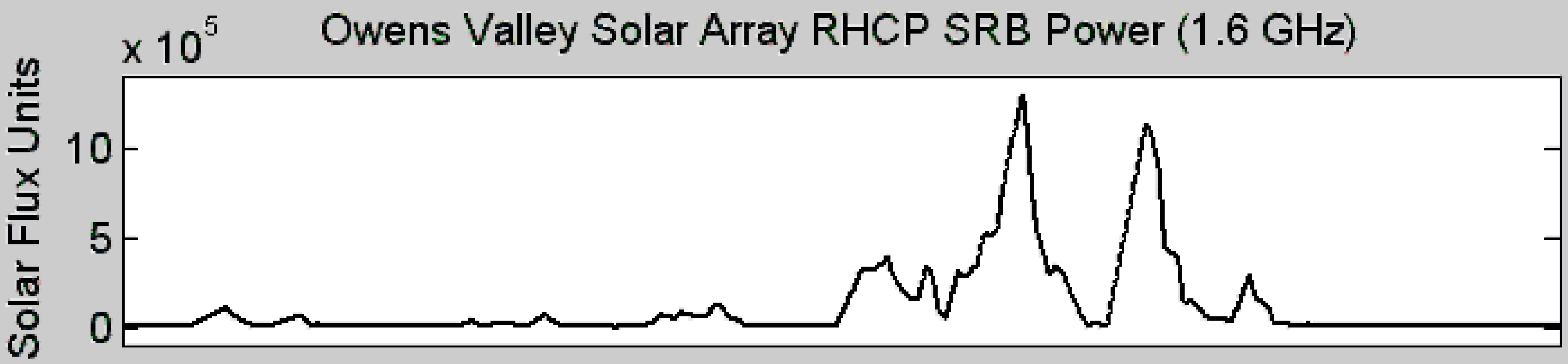




Cornell University

IGS Network, 6 December 2006





Outline

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- History
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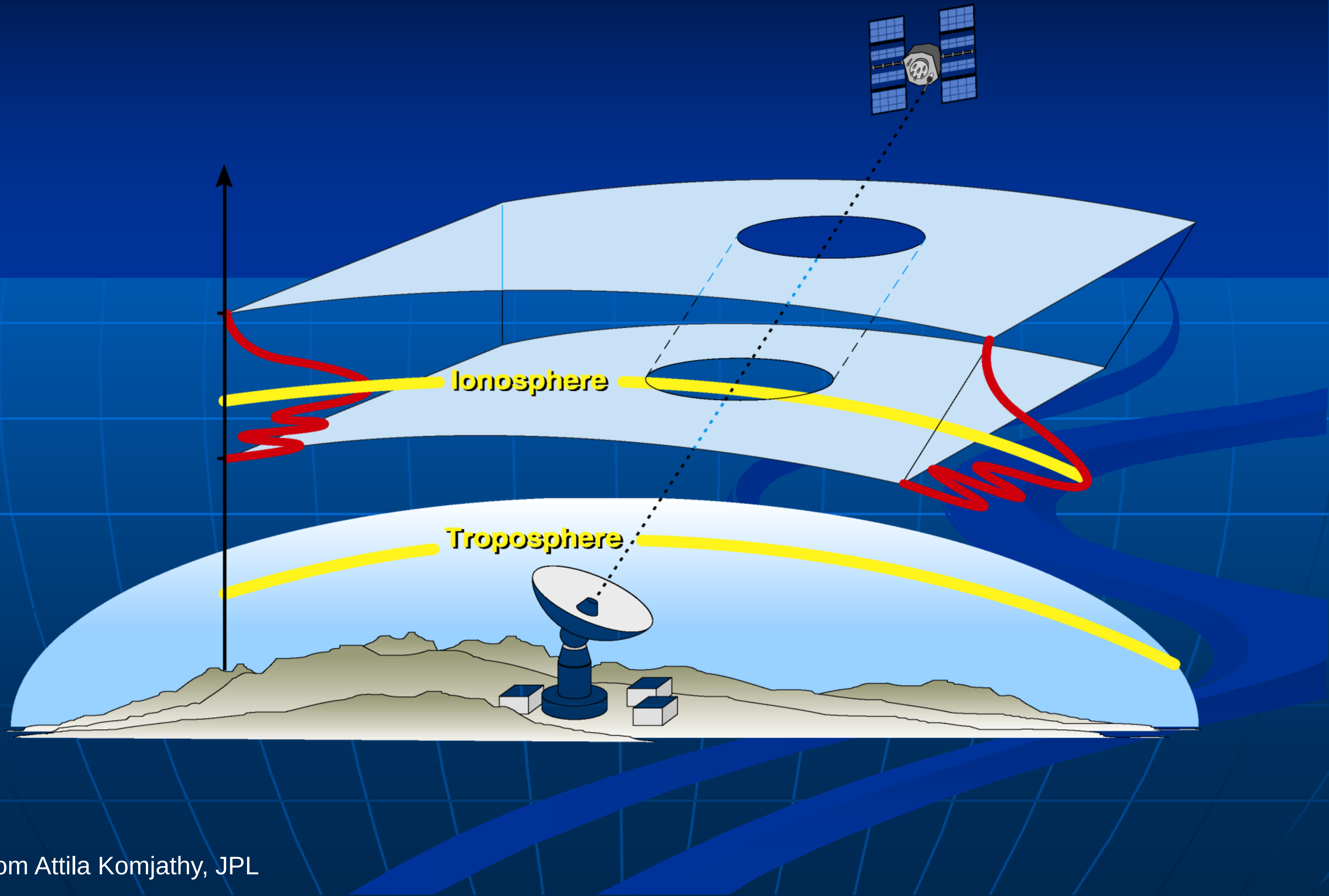
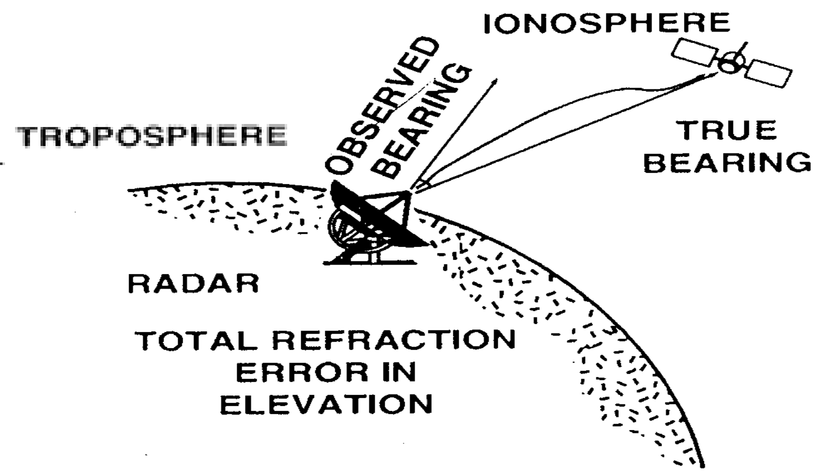
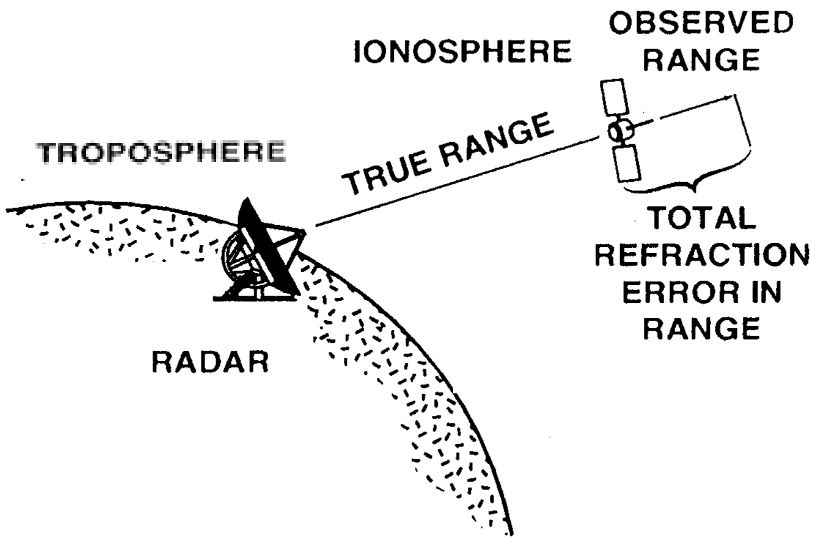
Atmospheric Propagation



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 $\bar{k}$ 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

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

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

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

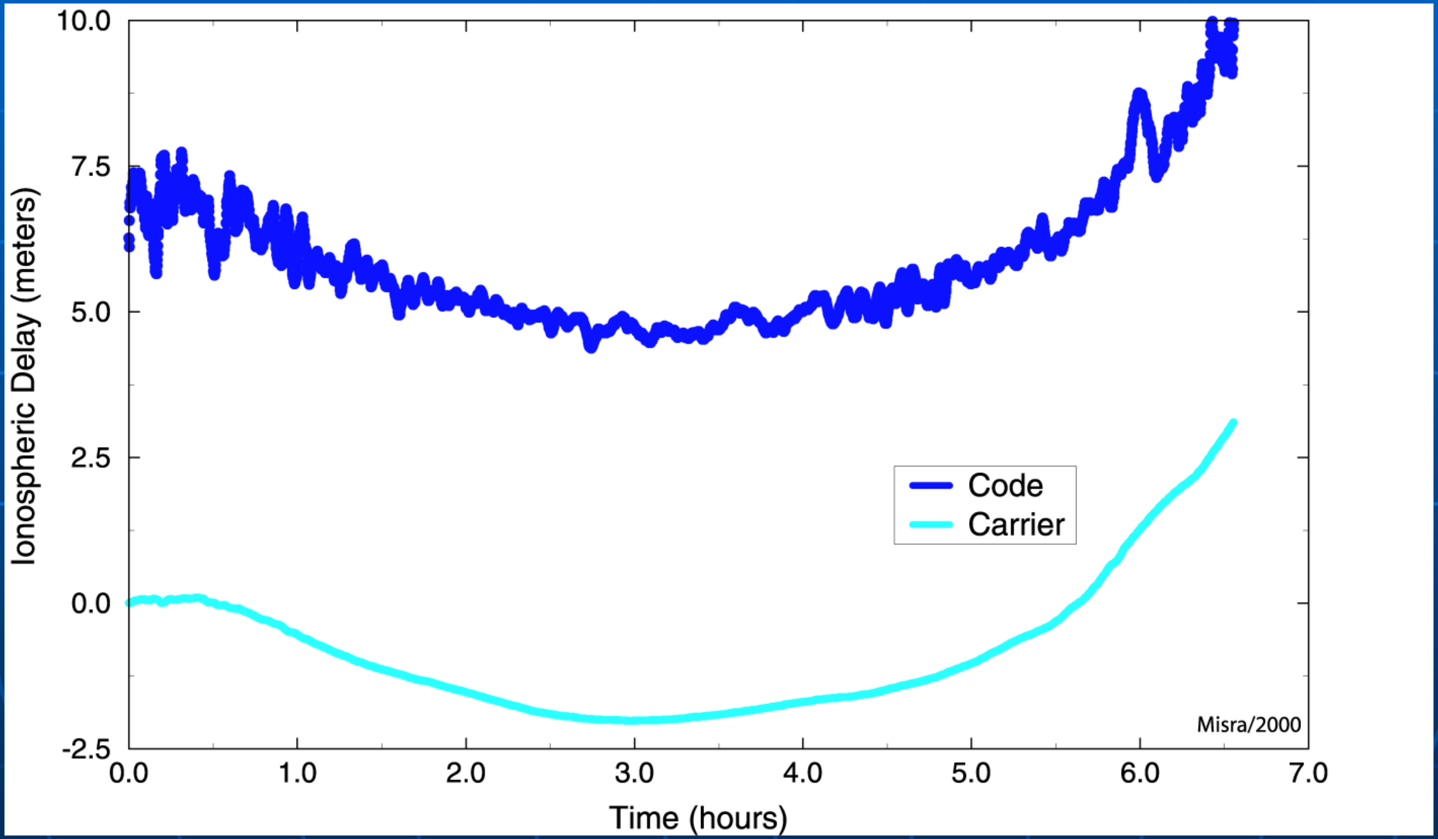
- **Total Electron Content**
- **Scintillation Parameters: S_4 and σ_Φ**

Space-Based Receivers

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

Total Electron Content (TEC) Estimation

Dual-Frequency Measurements



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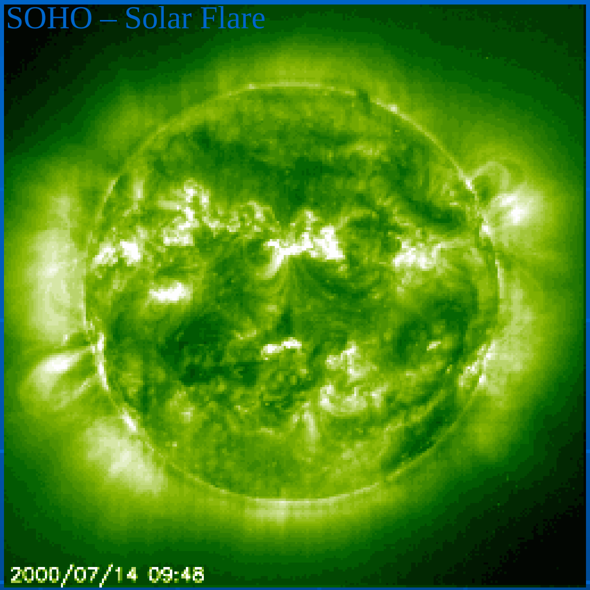
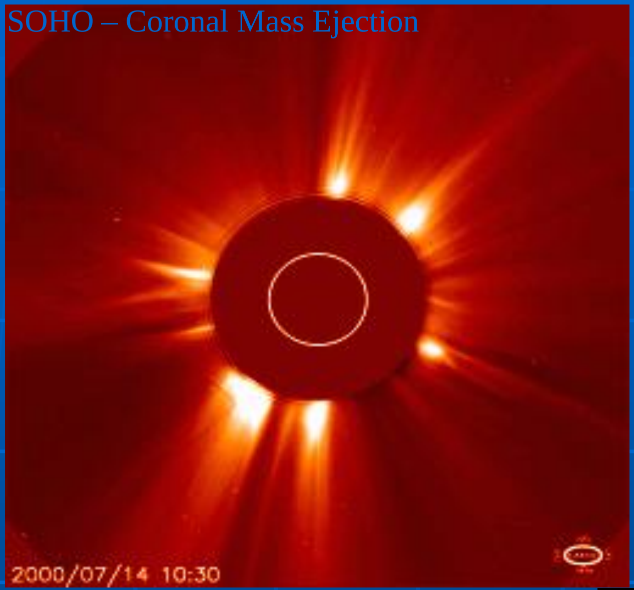
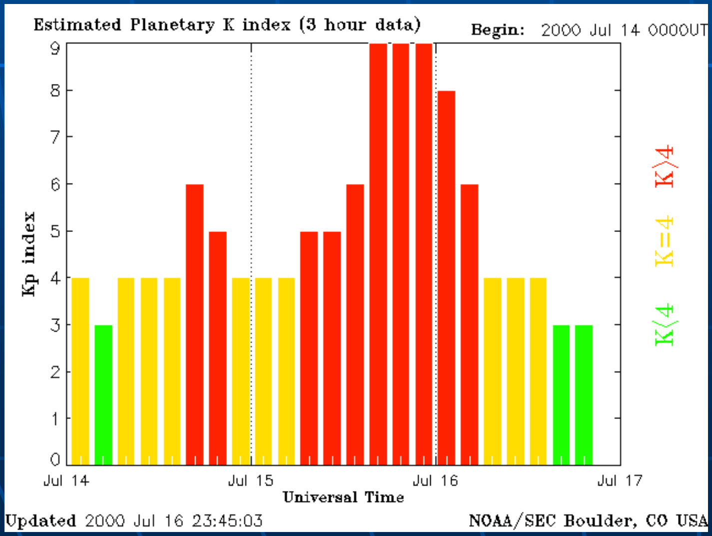
Solar Flare of 14 July 2000

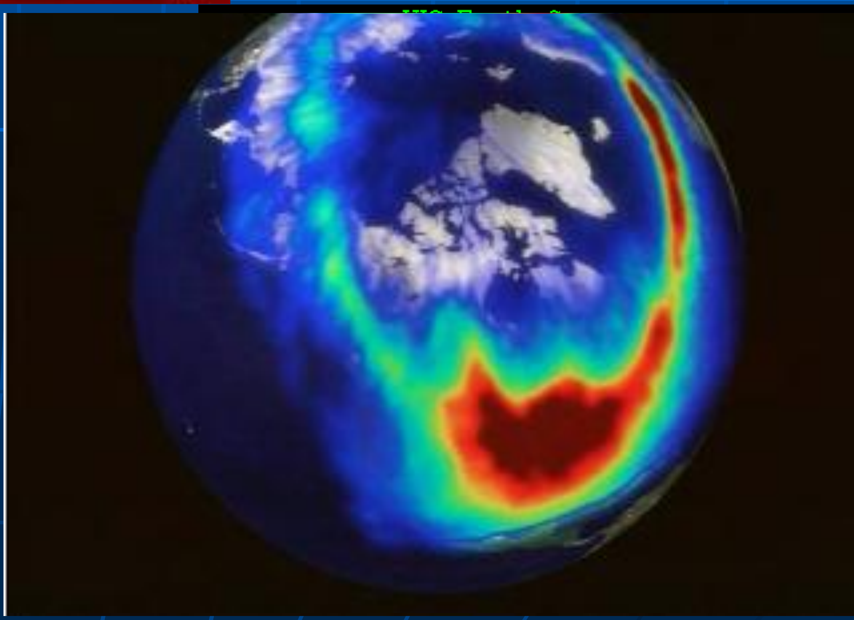




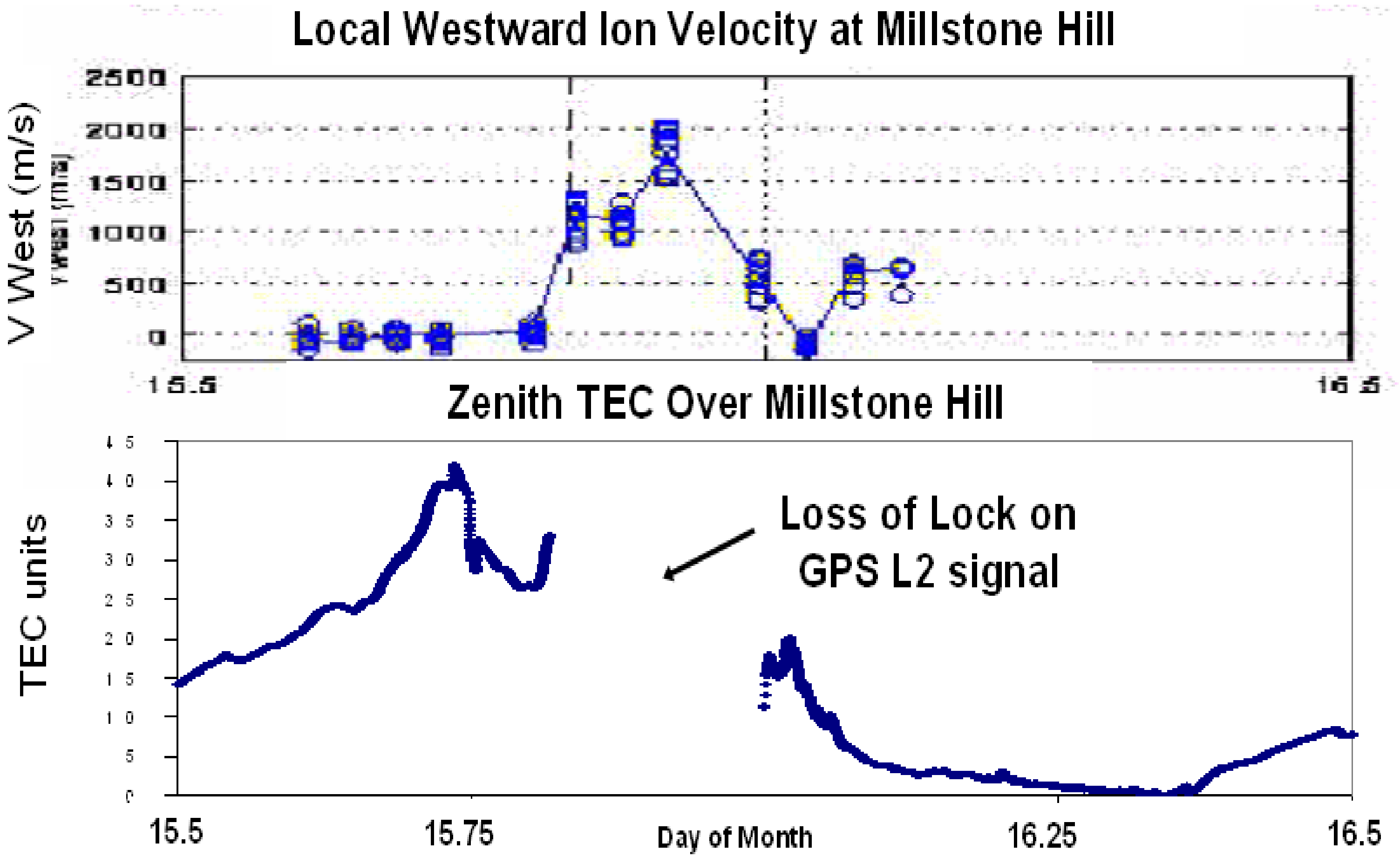
Solar Flare of 14 July 2000
Biggest Solar Storm in Nine Years

Caused very large magnetic storm and ionospheric effects

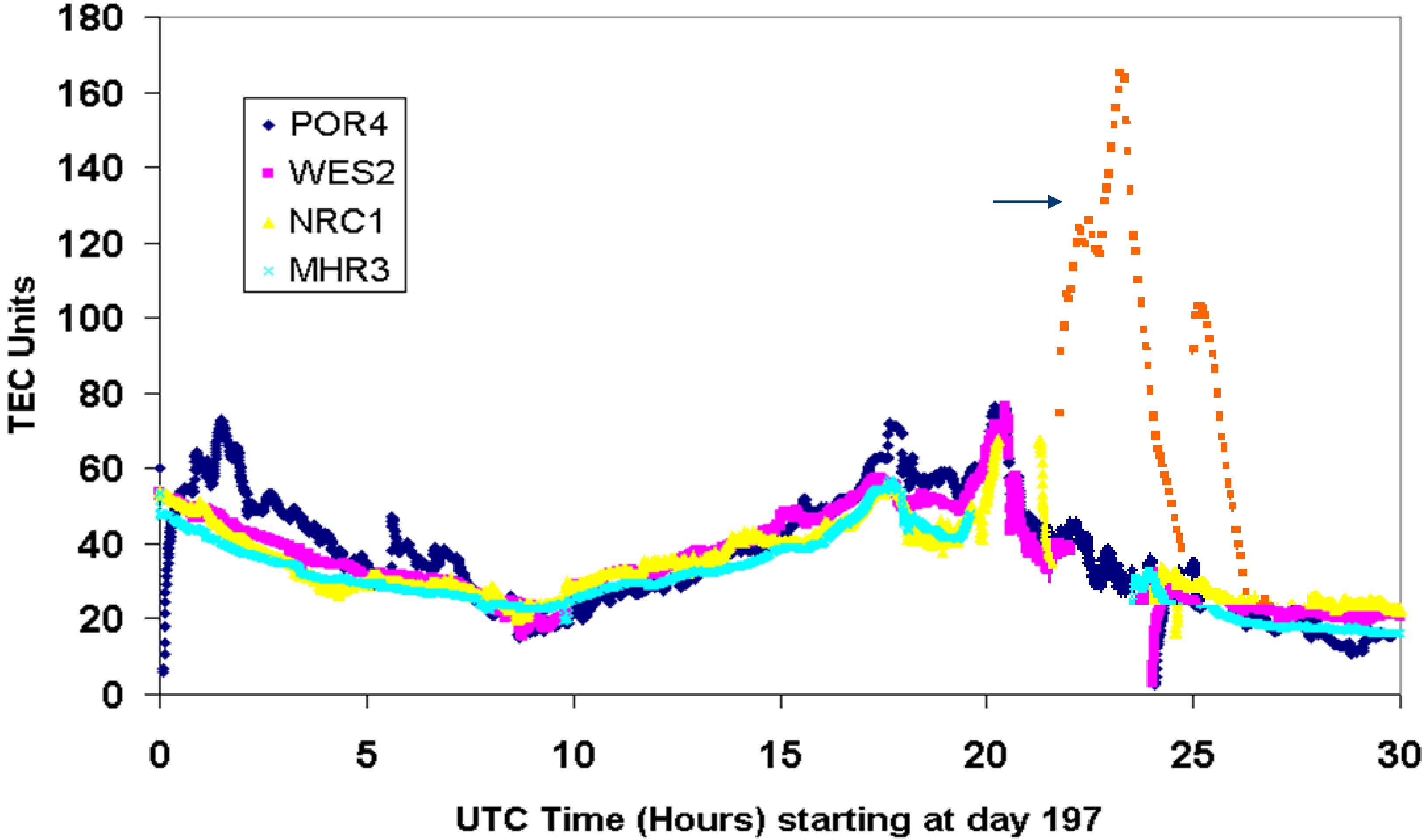




GPS Loss of Lock at Millstone Hill

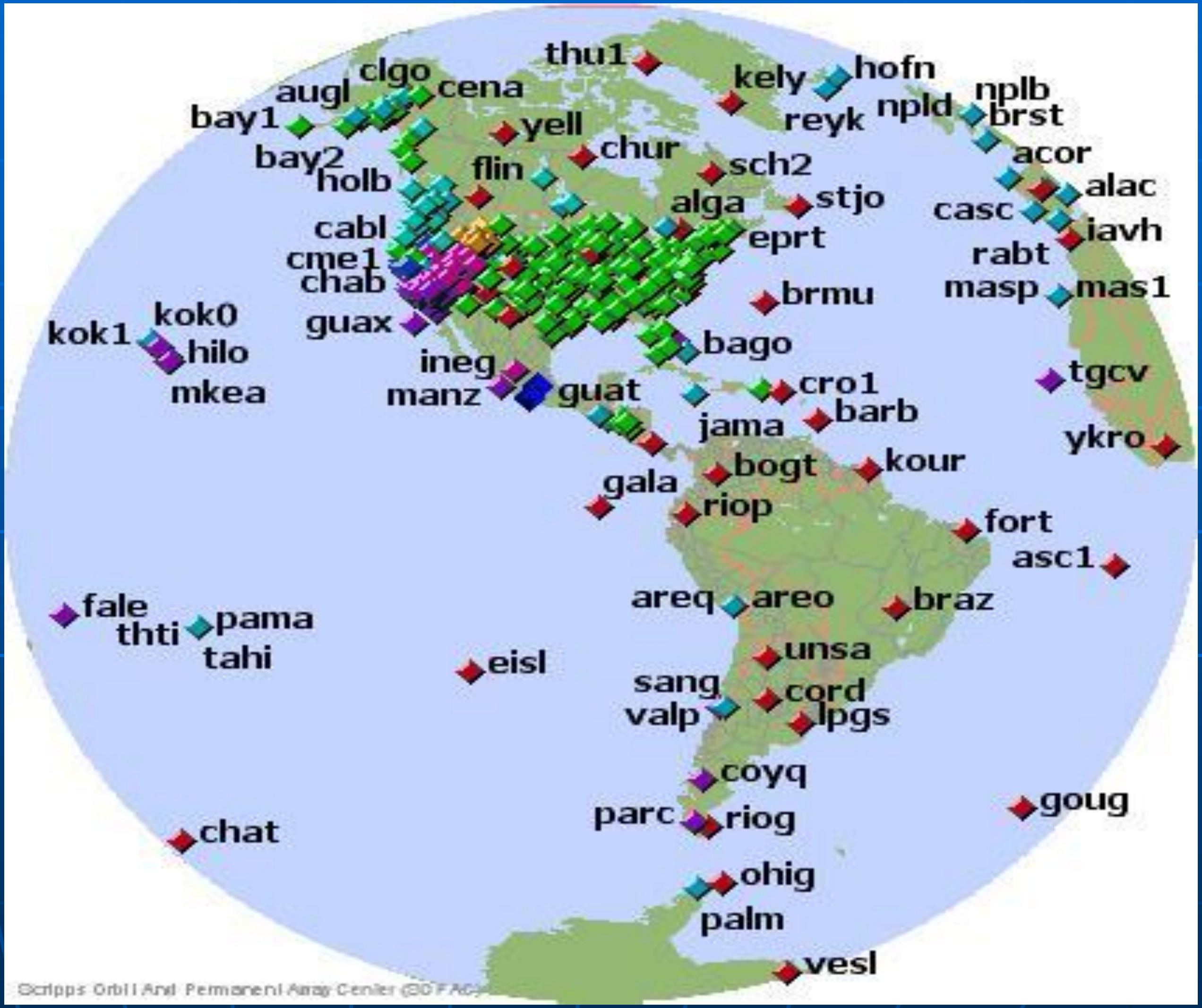


TEC Disturbances on 15 July 2000



Wide Area Distribution of 'Raw' Information

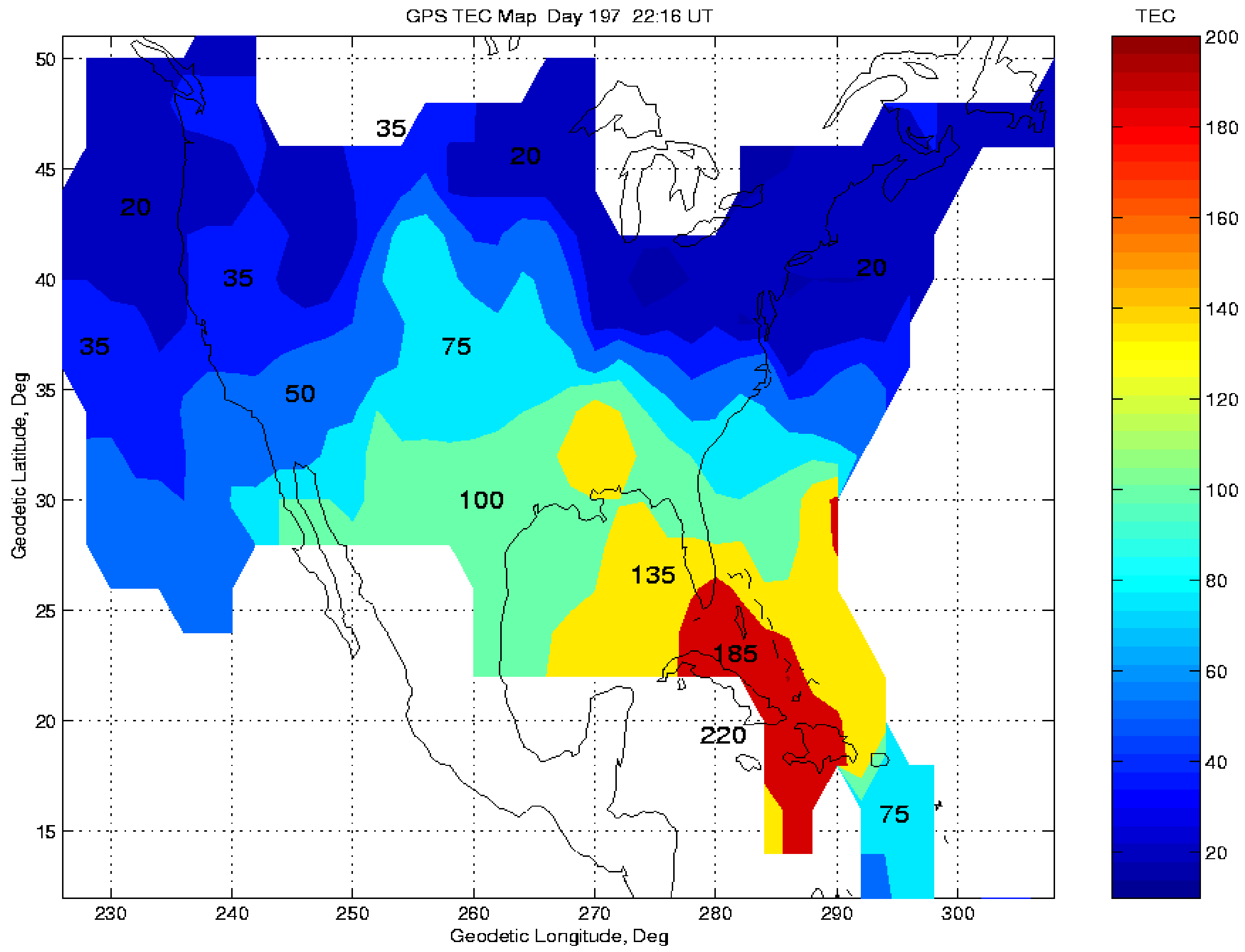
Distributed networks of sensors yield global physics unattainable with single-point measurements



[Coster et al, 2003]

GPS Total Electron Content Map

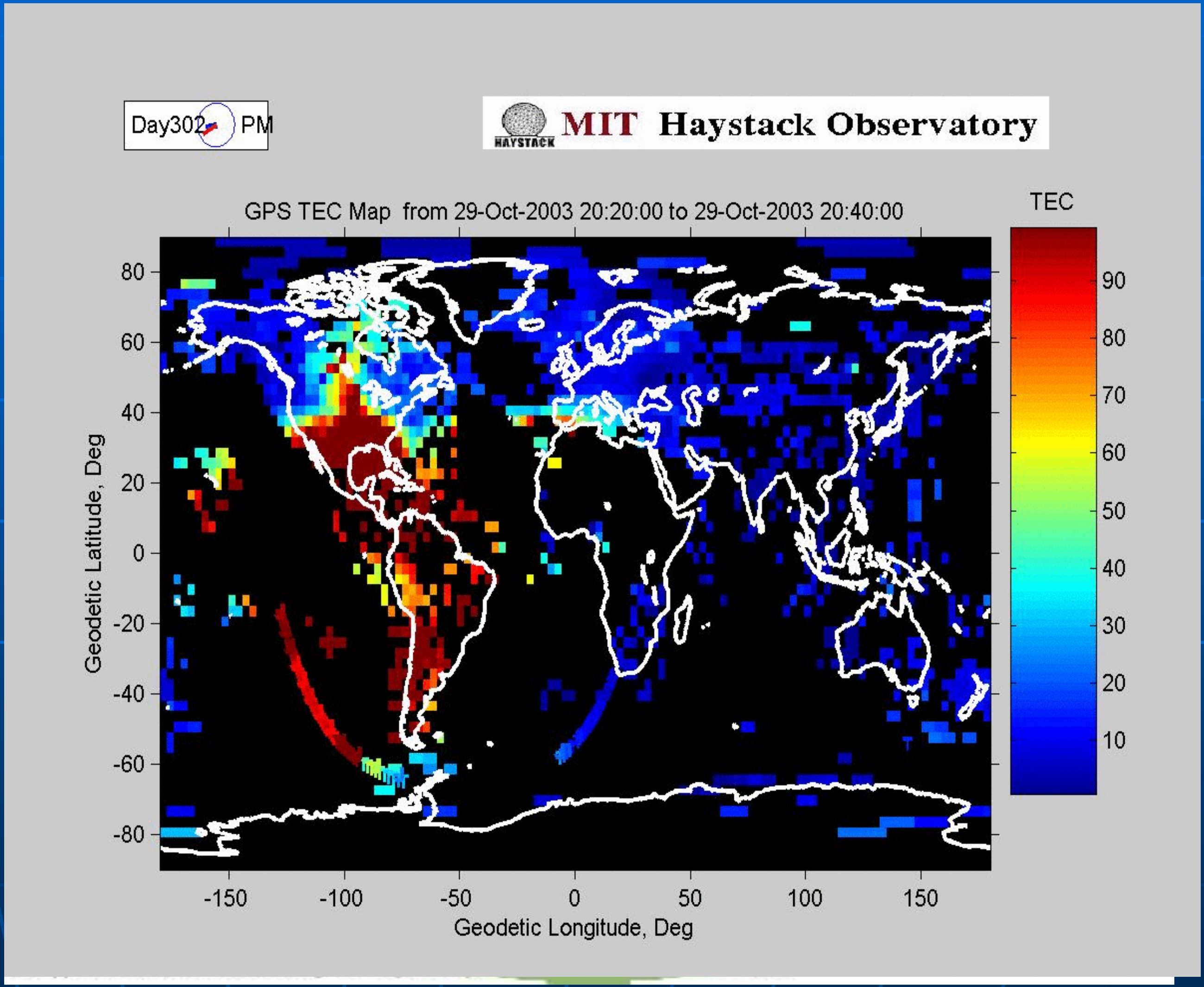
Illustration of Storm Enhanced Density



Wide Area Distribution of 'Raw' Information

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

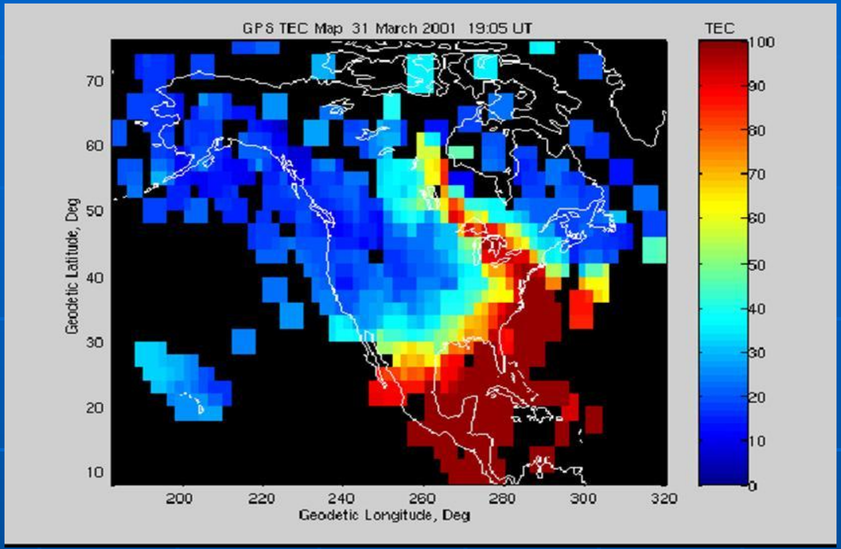
Example :
Global GPS-derived ionospheric mapping during geomagnetic disturbances

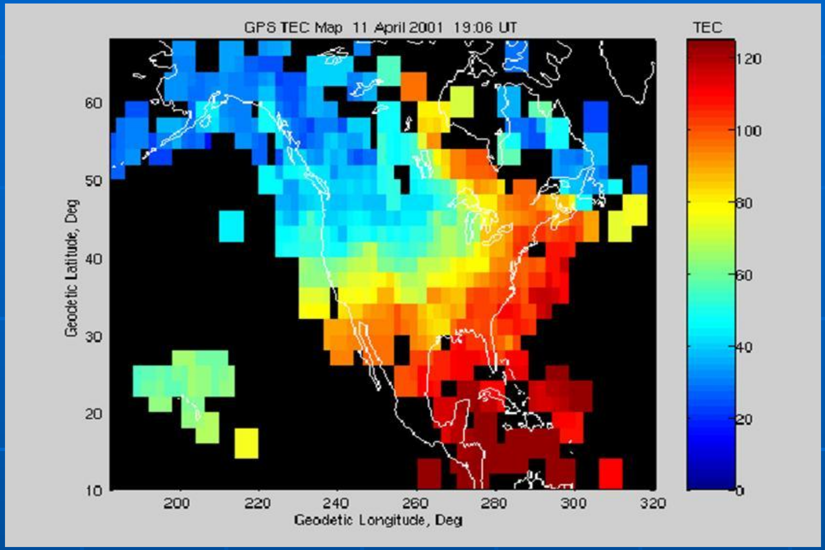


[Coster et al, 2003]

Day 90, 2001

Day 101, 2001





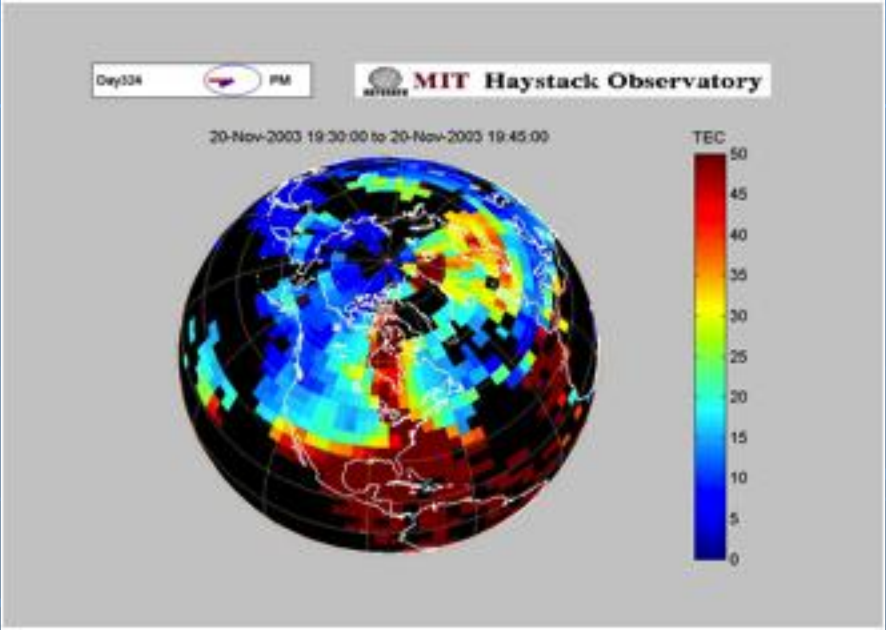
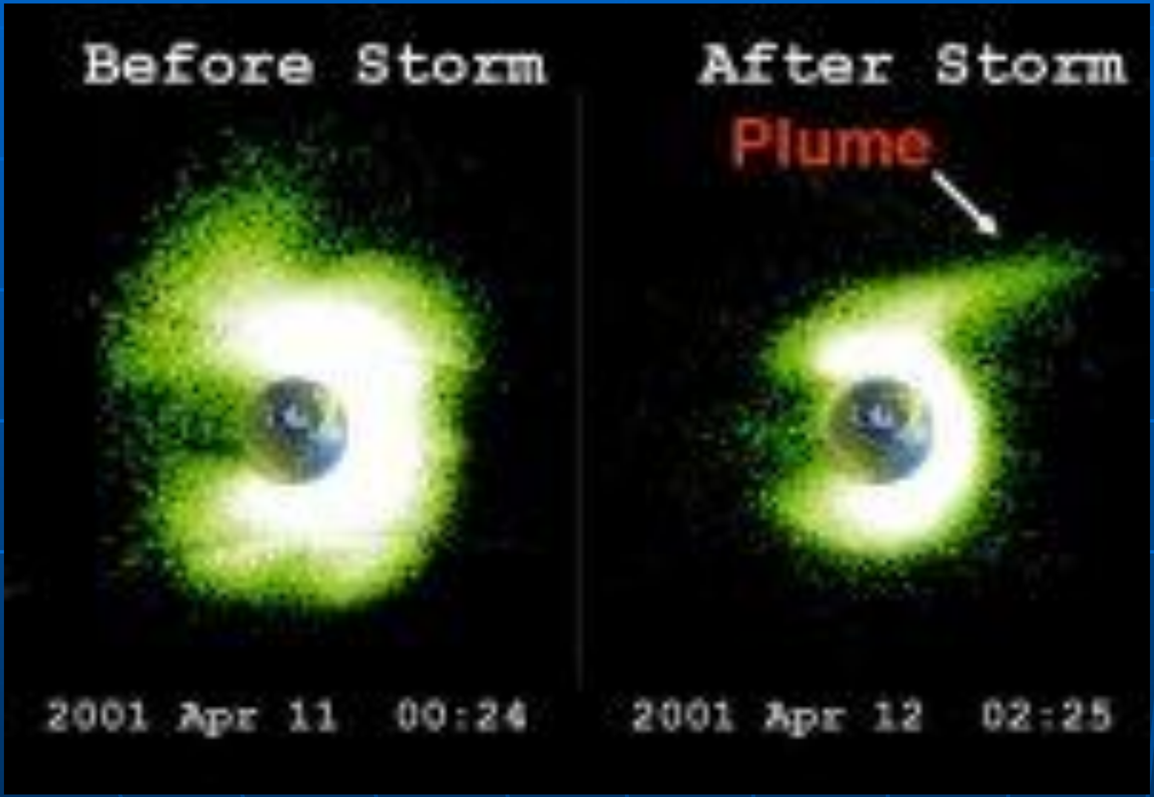
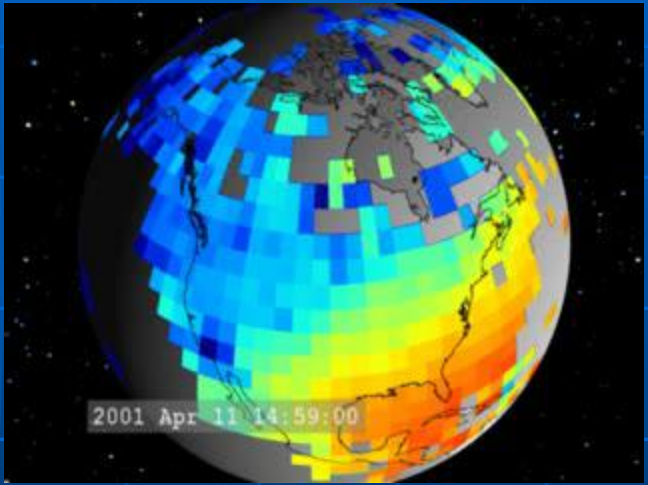


IMAGE Data of Plasmasphere





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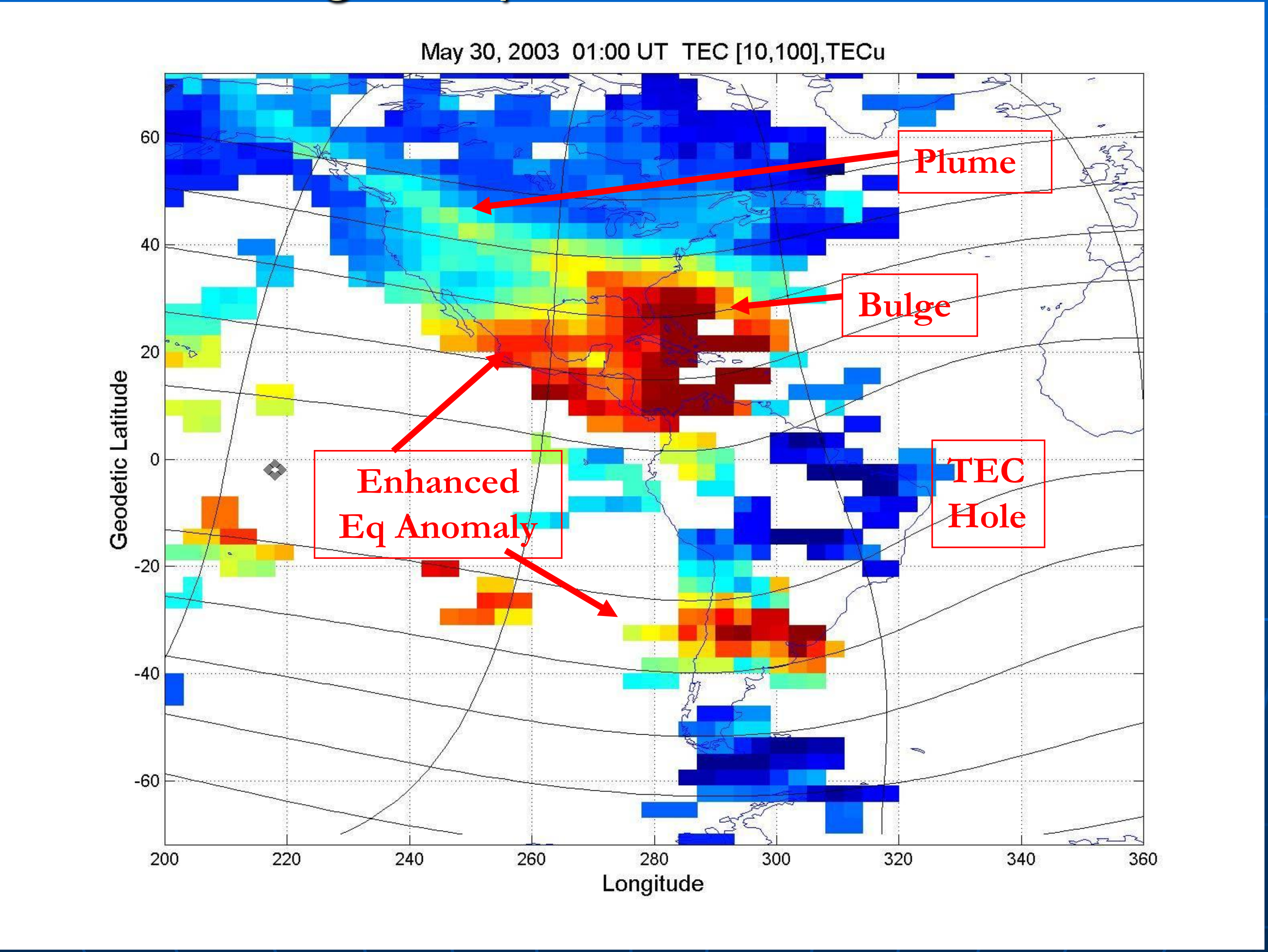
Inner Magnetosphere – Low Latitude View



Storm-time Electric Fields

- **Cross-tail electric fields energize and inject particles into the inner magnetosphere forming the disturbance Ring Current**

- **Strong penetration eastward electric field uplifts equatorial ionosphere**
  - **Equatorial anomaly enhanced**

- **Radial/Poleward Polarization Jet Electric Fields form (Sub Auroral Polarization Stream). As the Polarization Stream overlaps the outer plasmasphere**
  - **Storm-Enhanced Density (SED)**
  - **Detached plasmas/plasma tails**

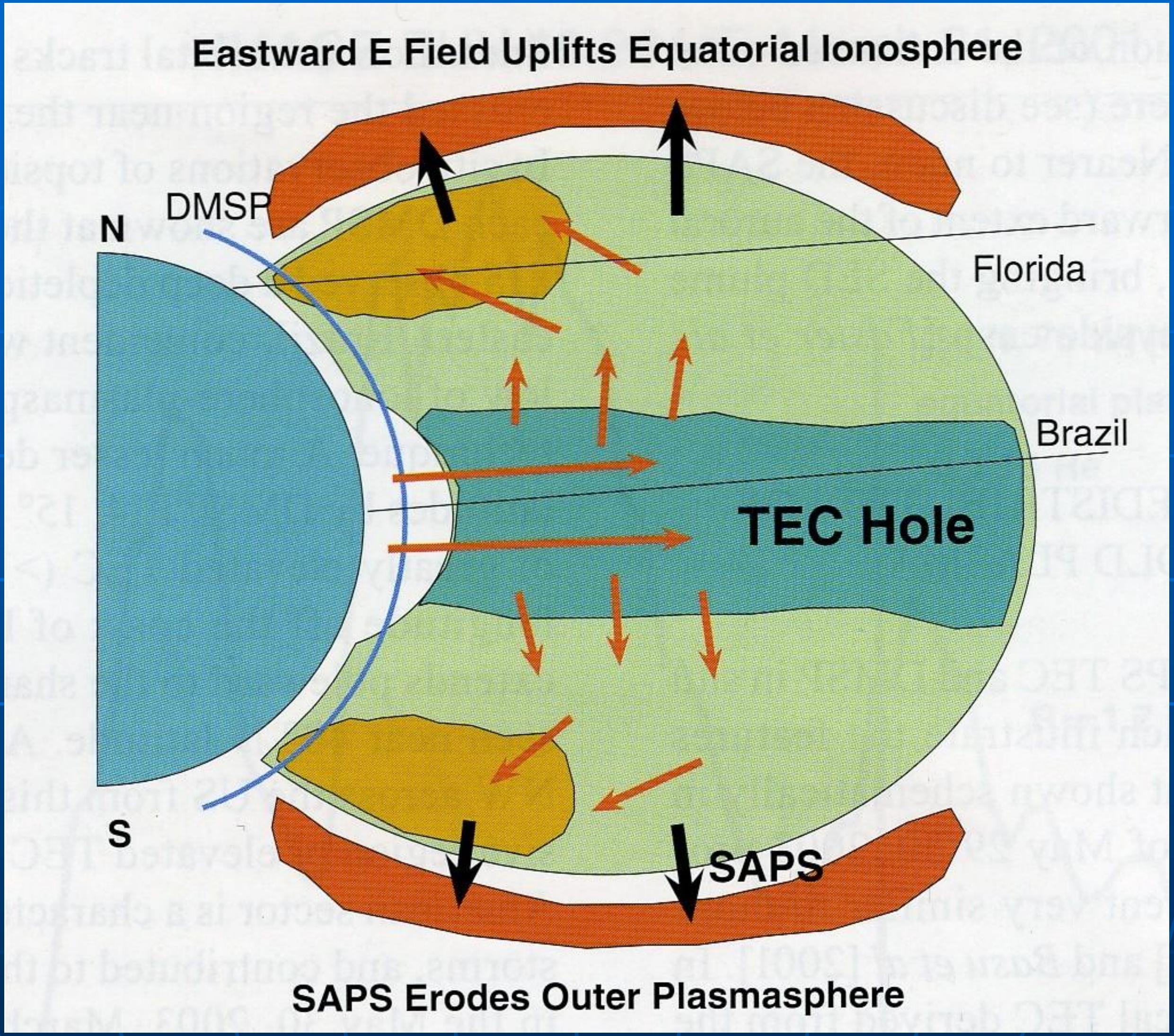
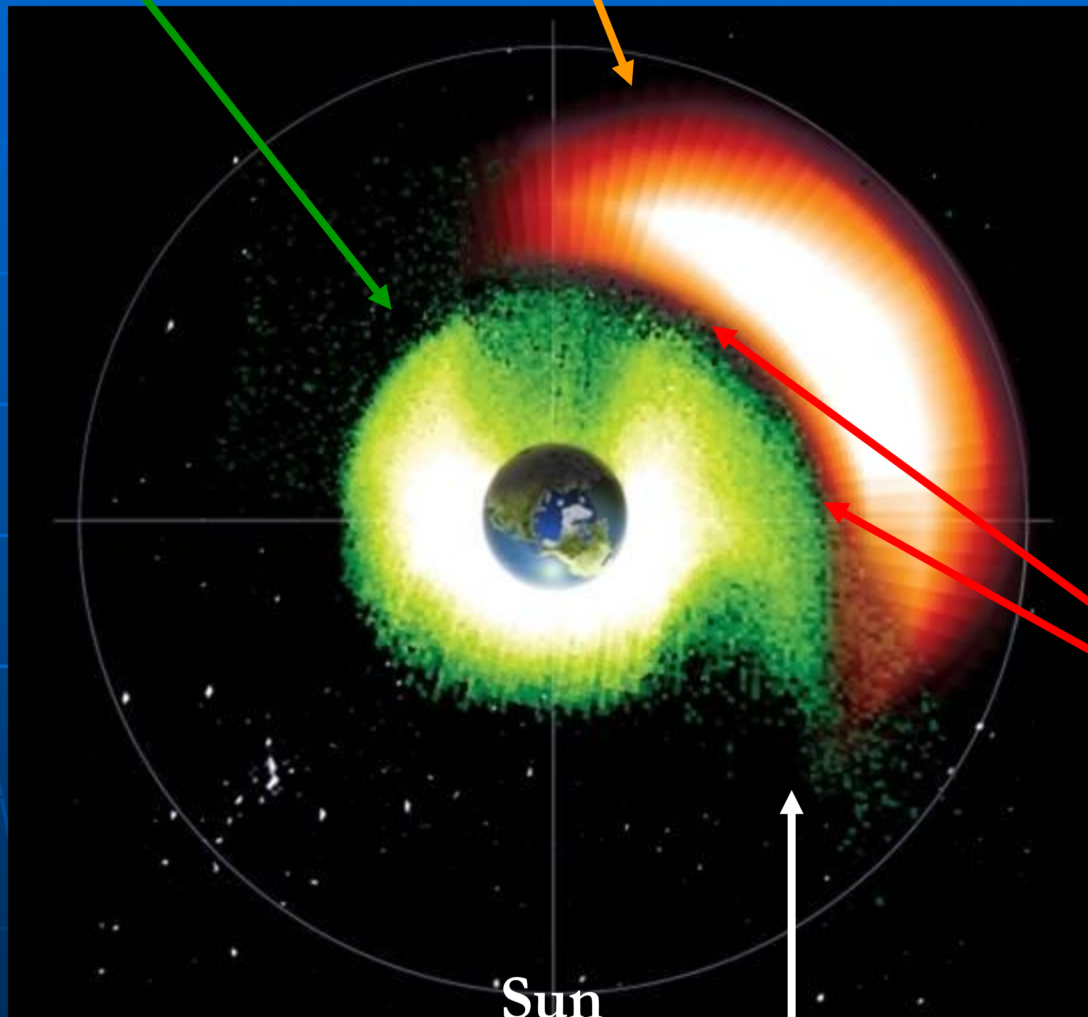


Figure courtesy of J. Foster

Plasmasphere / Ring Current Interactions

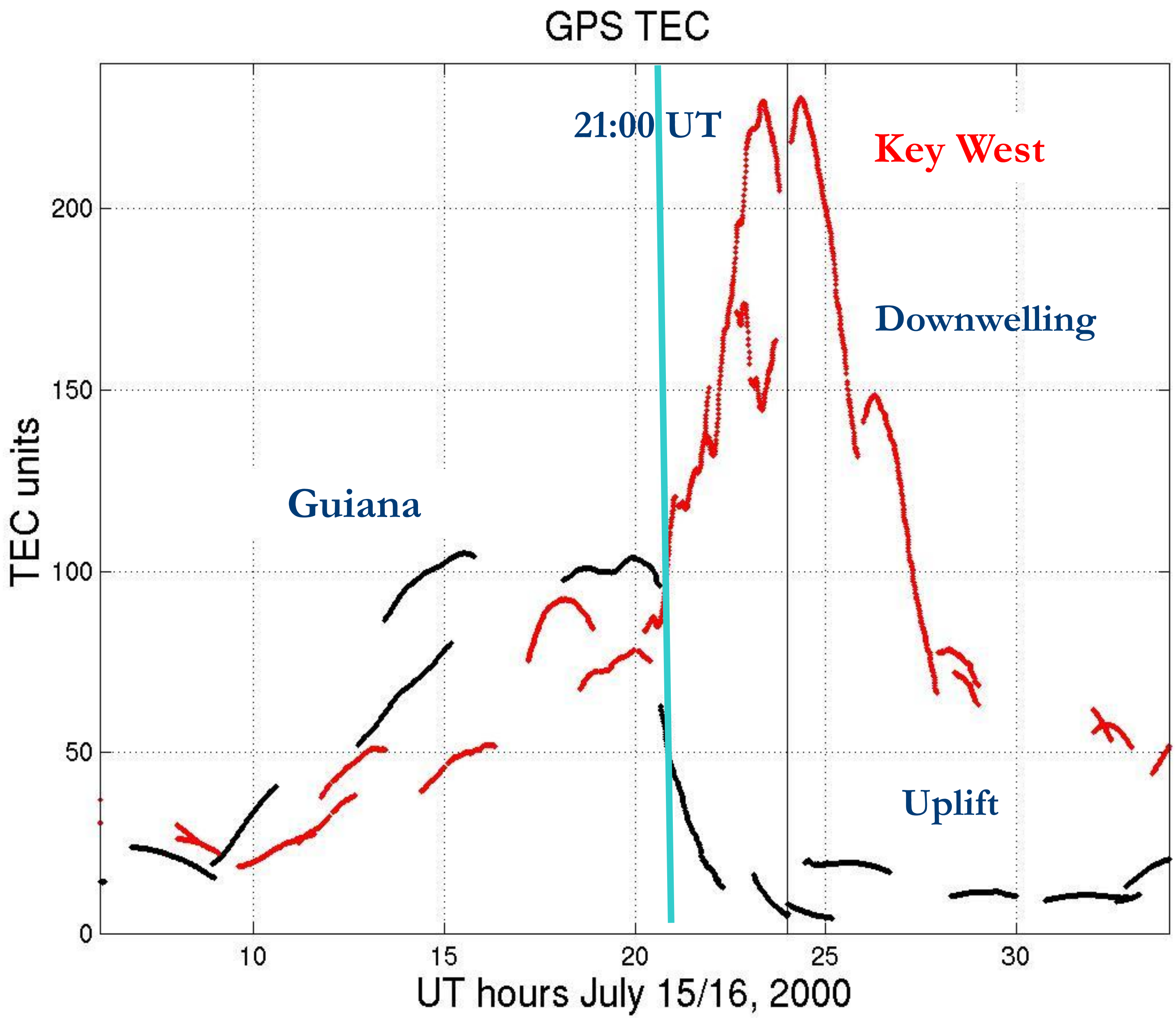


April 17, 2002
NASA IMAGE

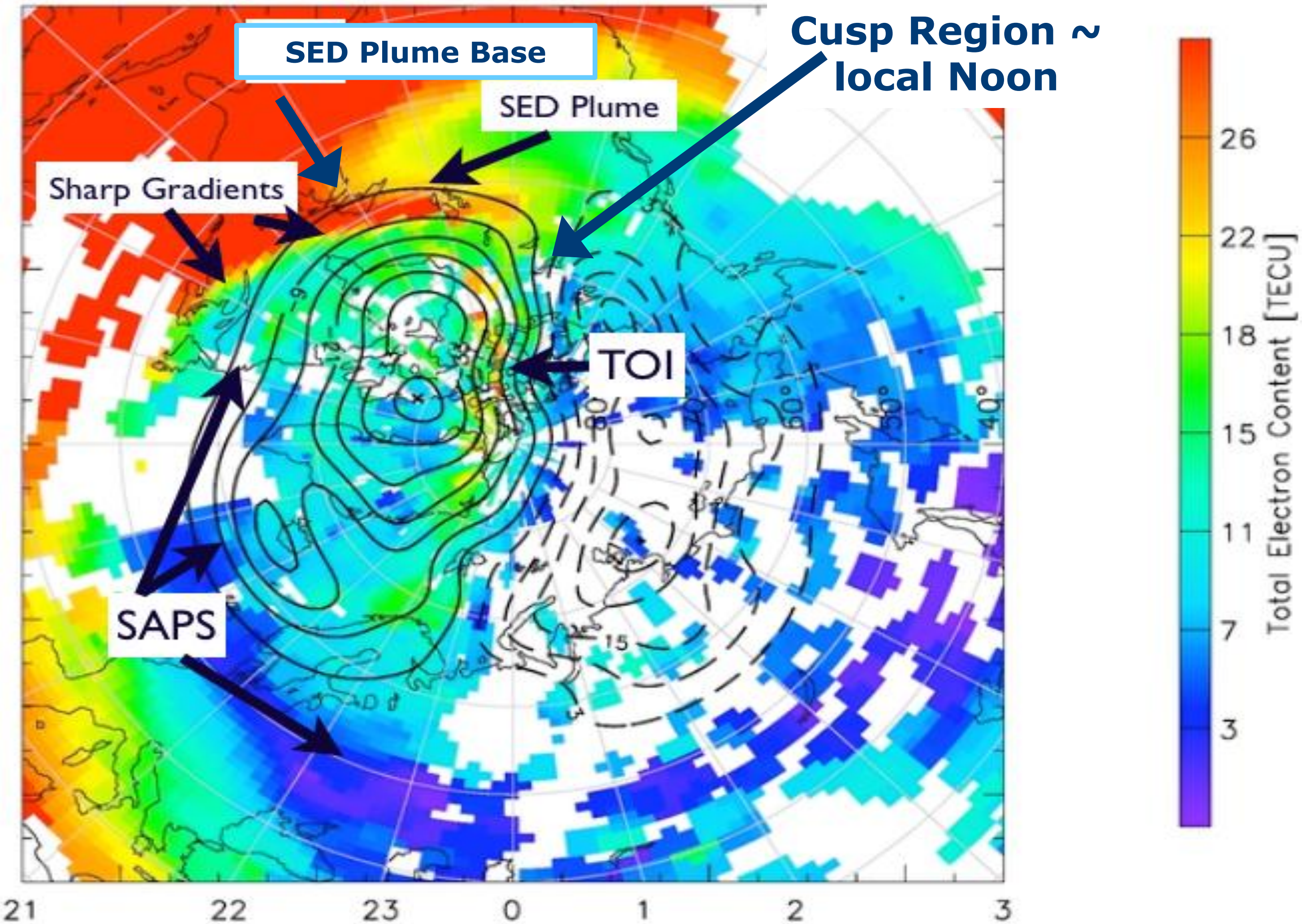
SAPS Channel

Plasmasphere Erosion Plume

(Merged image courtesy J. Goldstein)


GPS TEC
21:00 UT
Key West
Downwelling
Guiana
Uplift
TEC units
200
150
100
50
0
10
15
20
25
30
UT hours July 15/16, 2000

Common Features observed in TEC during geomagnetically disturbed conditions



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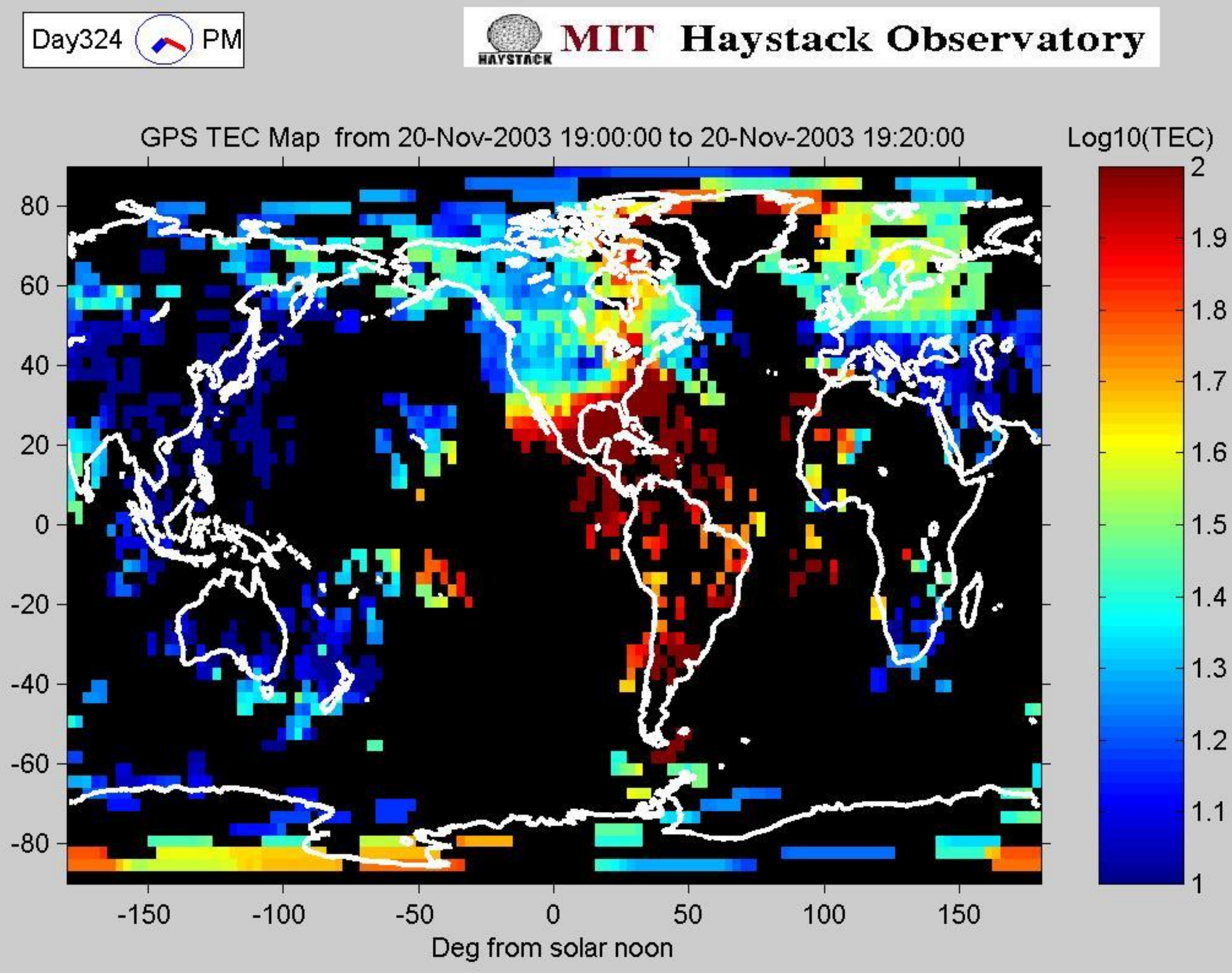
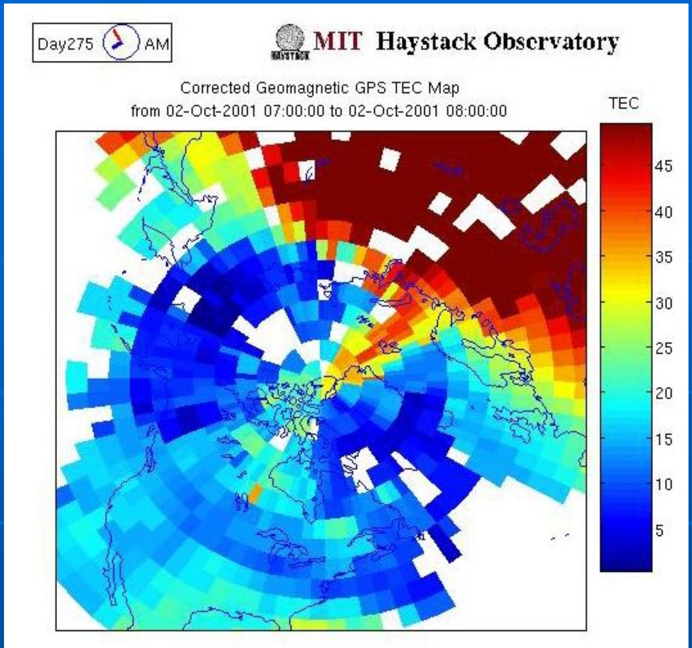
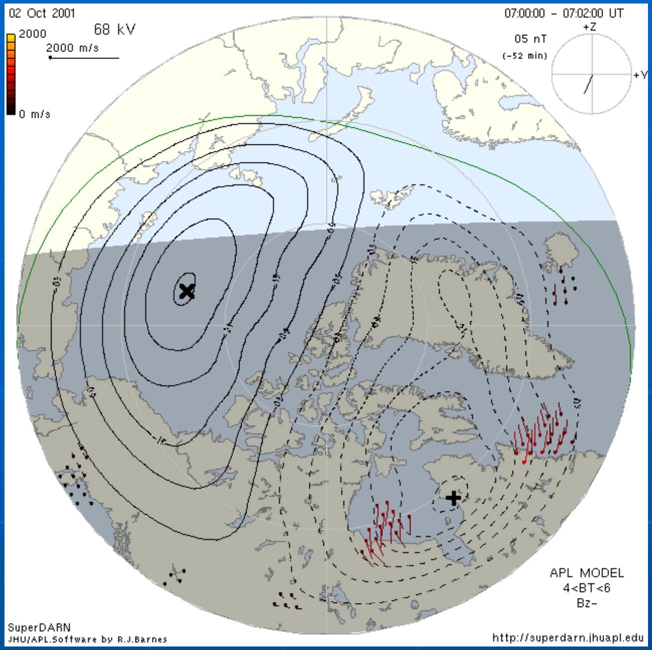

Day324
PM
MIT Haystack Observatory
HAYSTACK
GPS TEC Map from 20-Nov-2003 19:00:00 to 20-Nov-2003 19:20:00
Log10(TEC)
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150
Deg from solar noon
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1

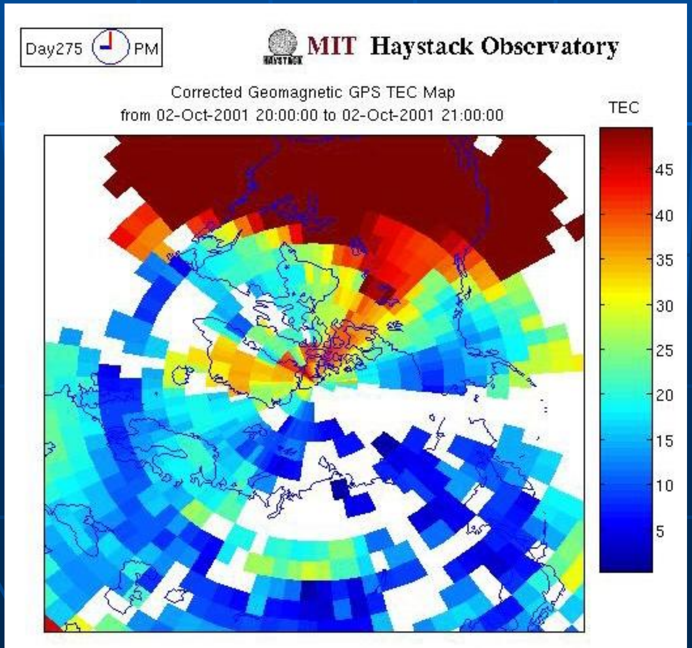
Northern Europe and American Sector SED Plumes

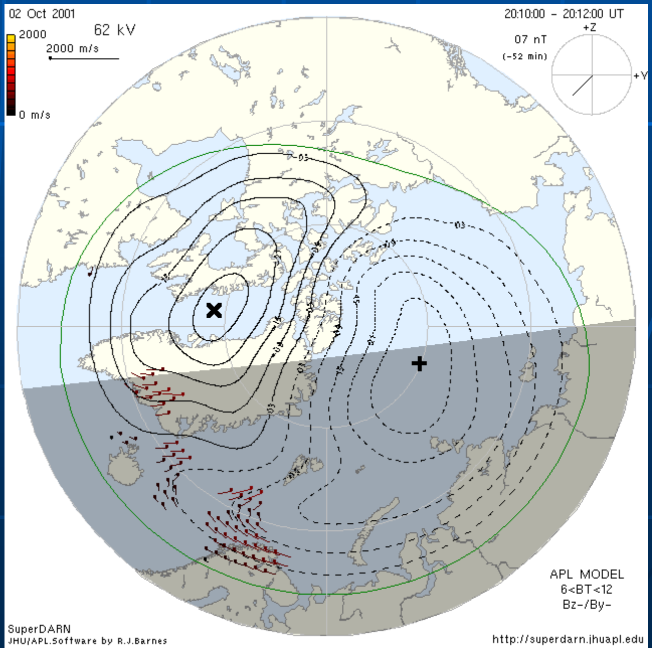
Northern Europe



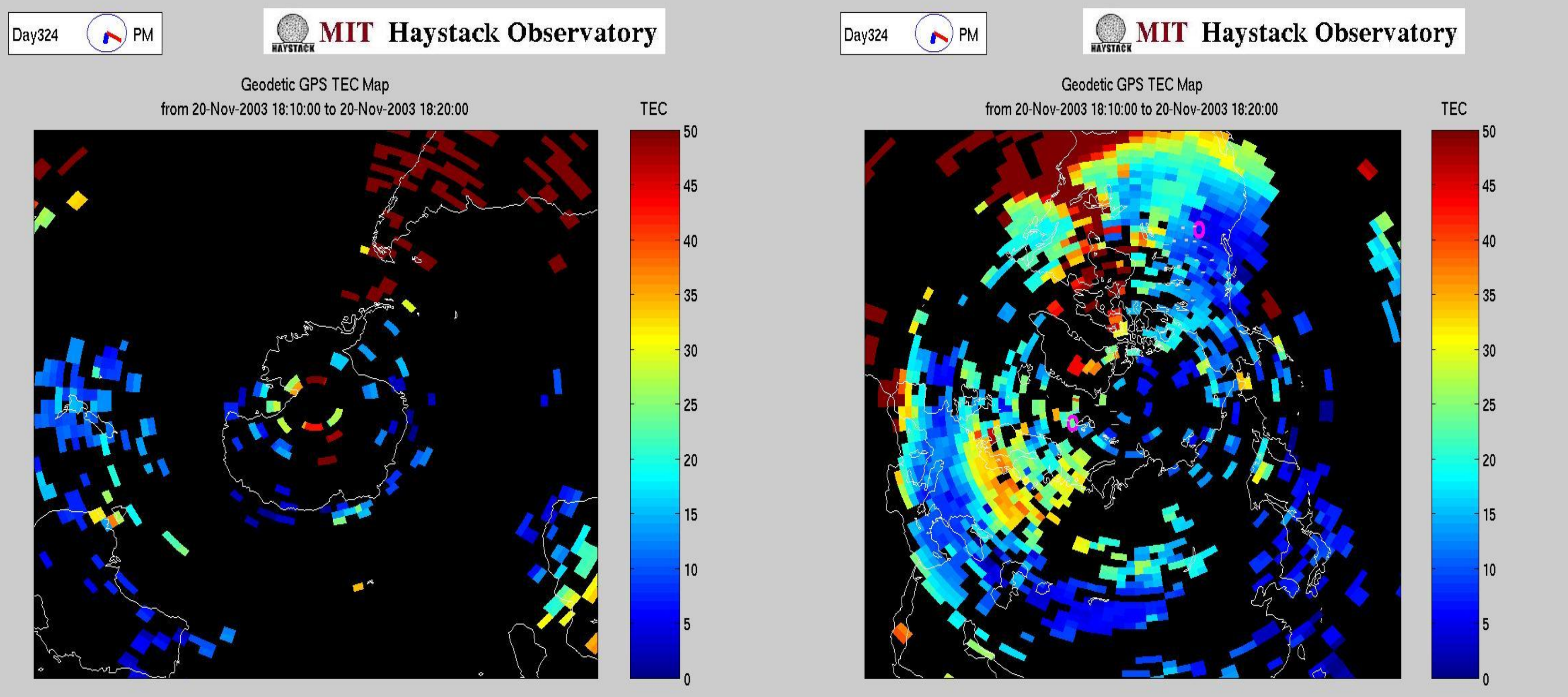


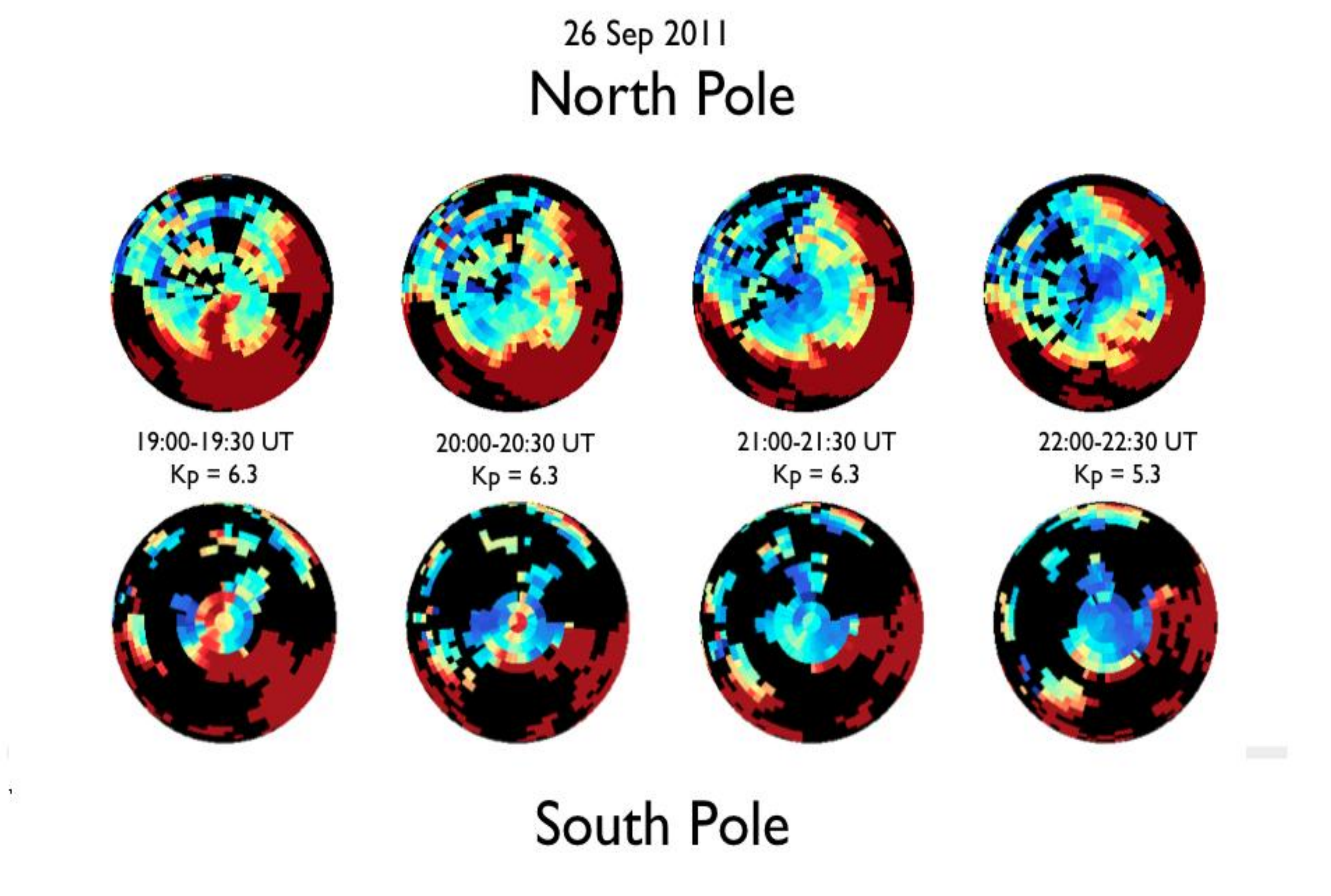
American Sector



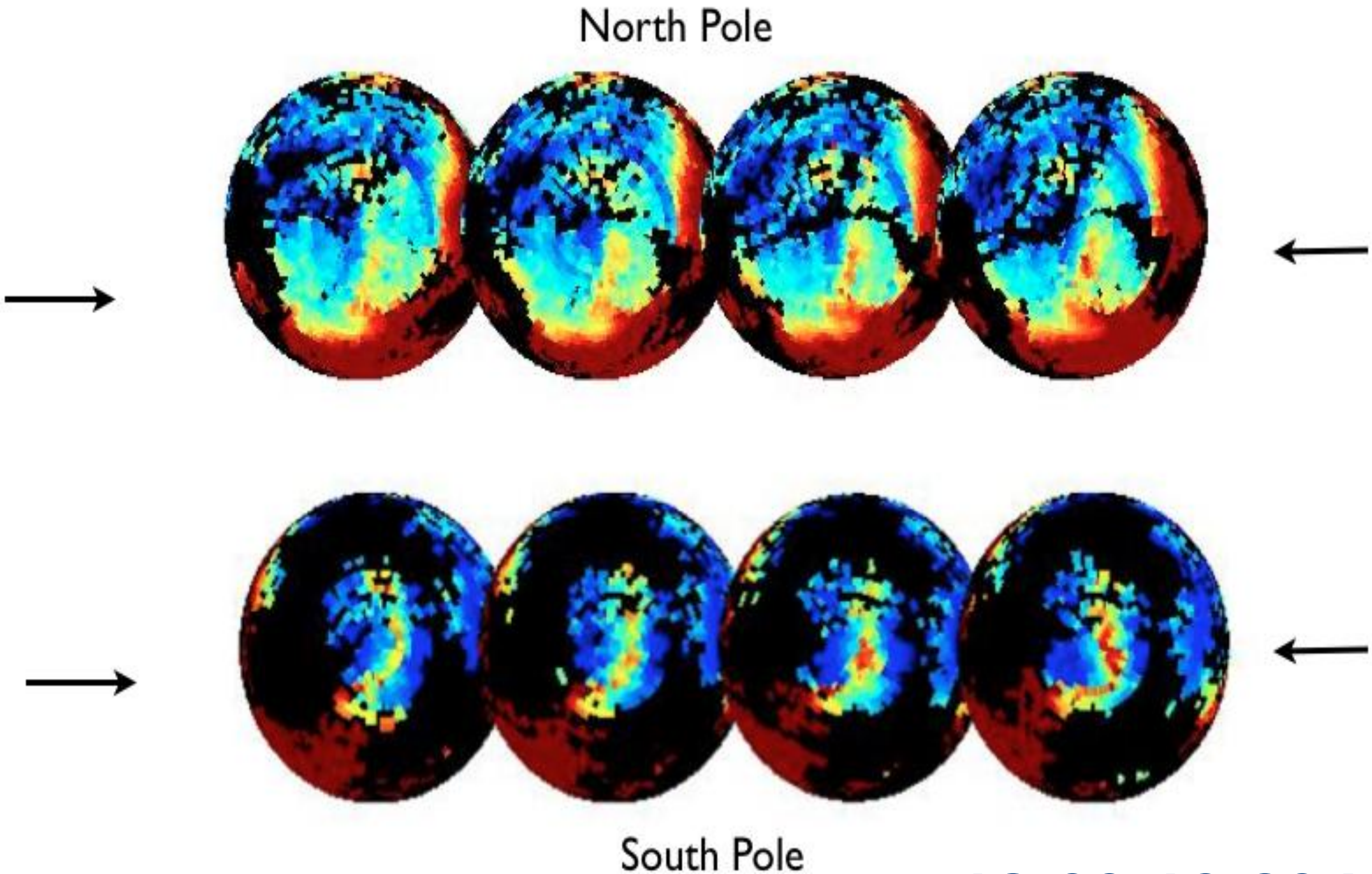


20 Nov 2003 18:20 UT




26 Sep 2011
North Pole
19:00-19:30 UT
Kp = 6.3
20:00-20:30 UT
Kp = 6.3
21:00-21:30 UT
Kp = 6.3
22:00-22:30 UT
Kp = 5.3
South Pole

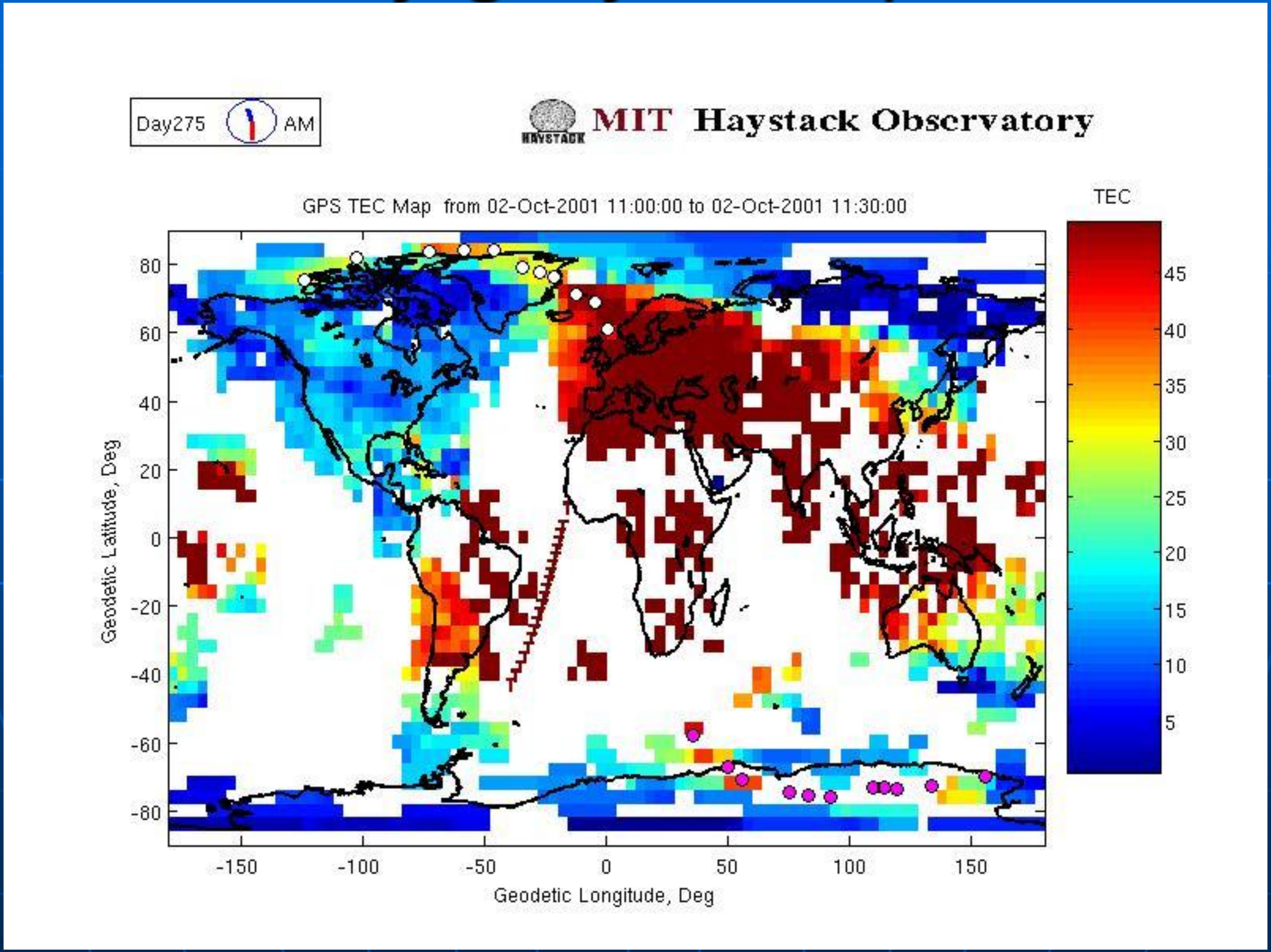
Location of Base of Plume stays fixed in longitude



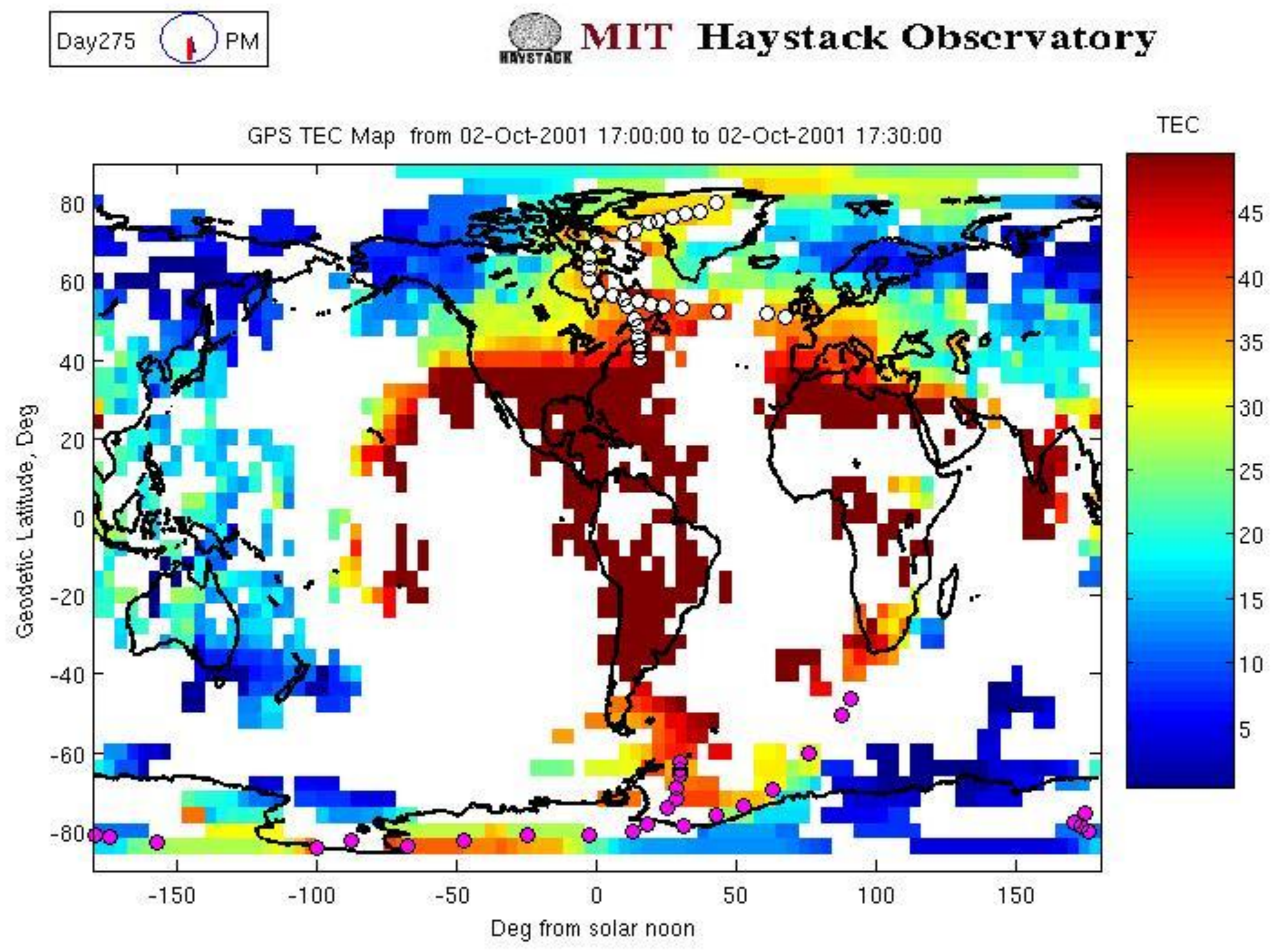
17 March 2013

18:00-19:20 UT

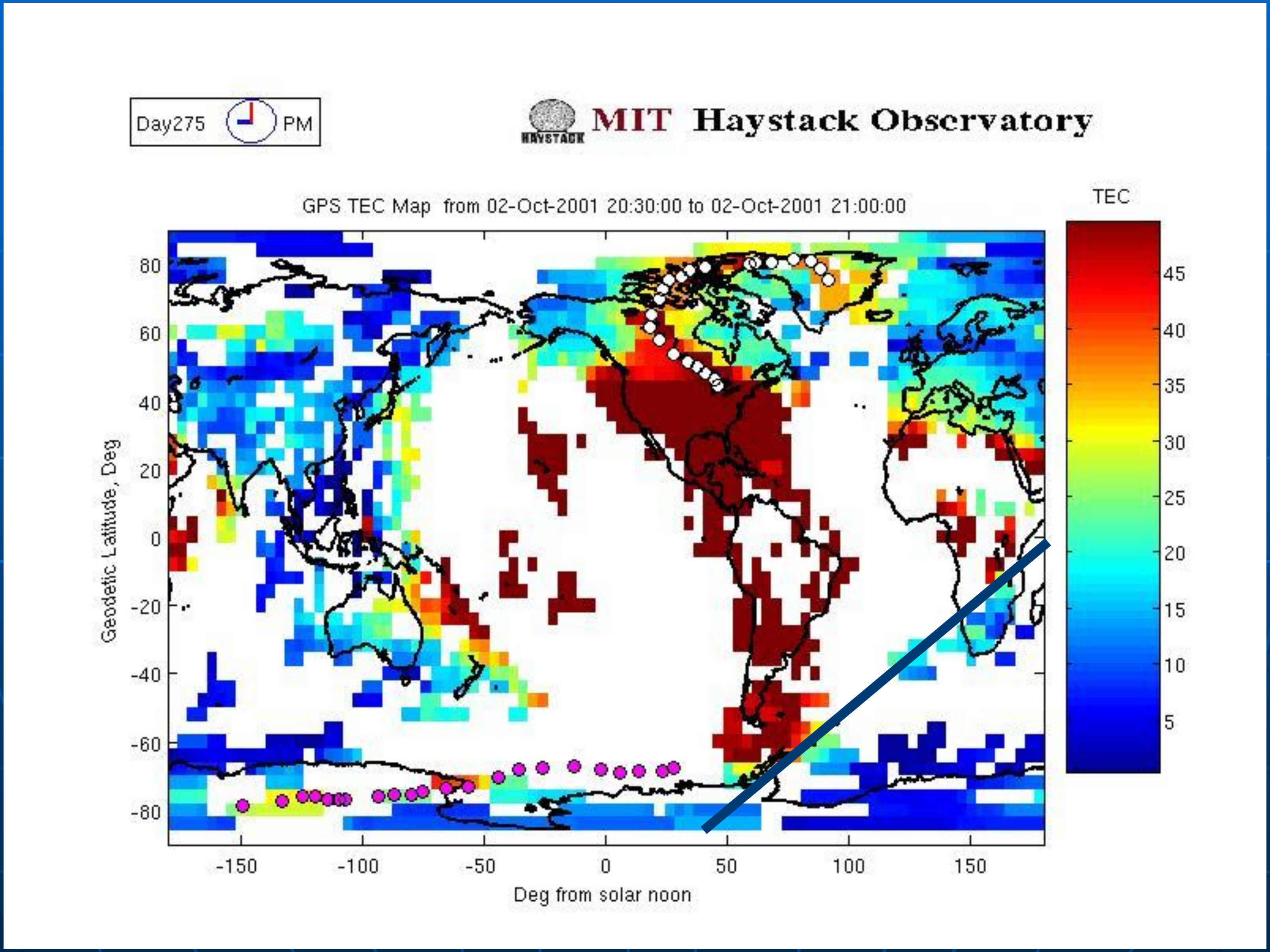
Conjugacy Examples

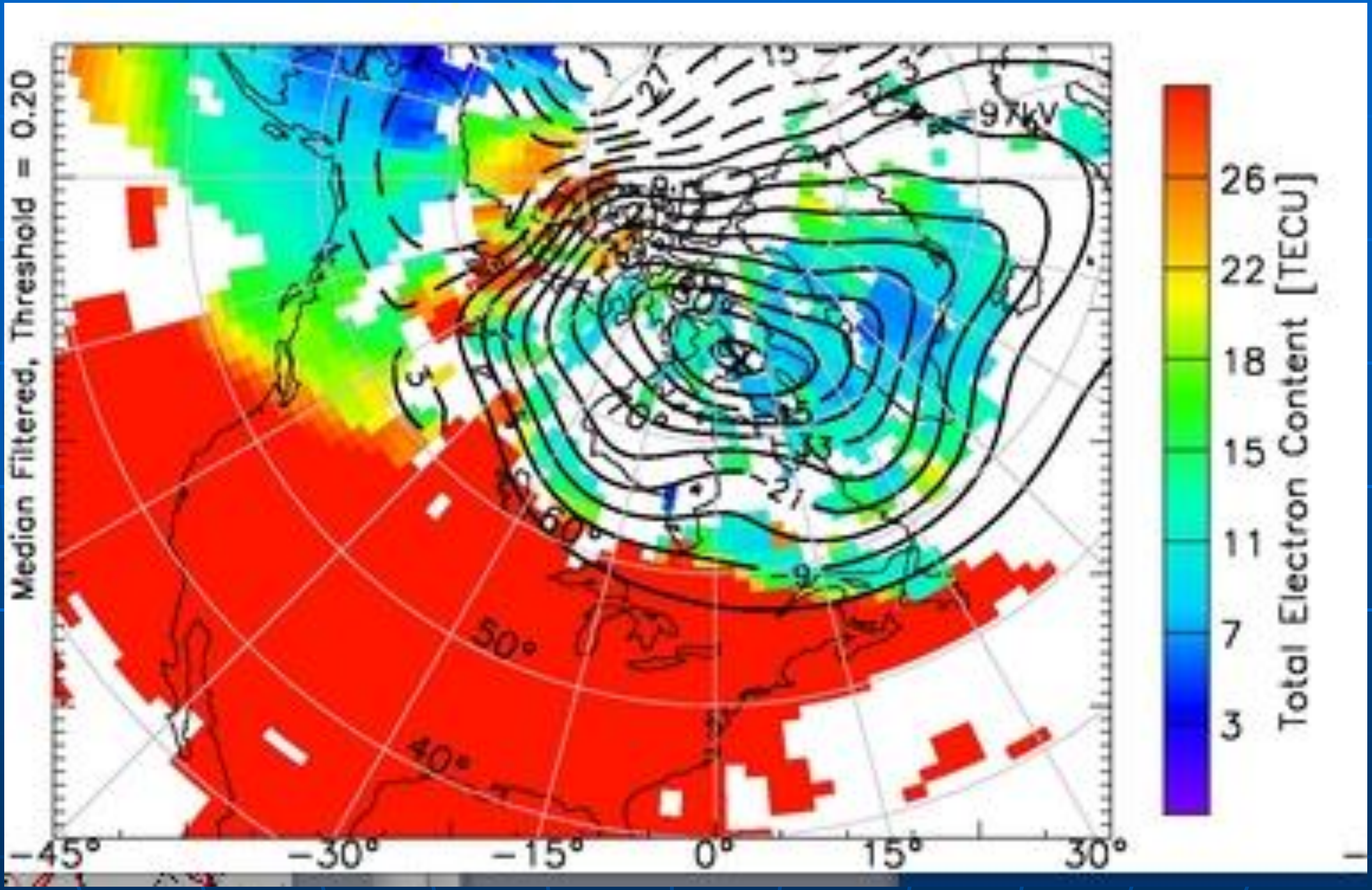


Conjugacy Examples

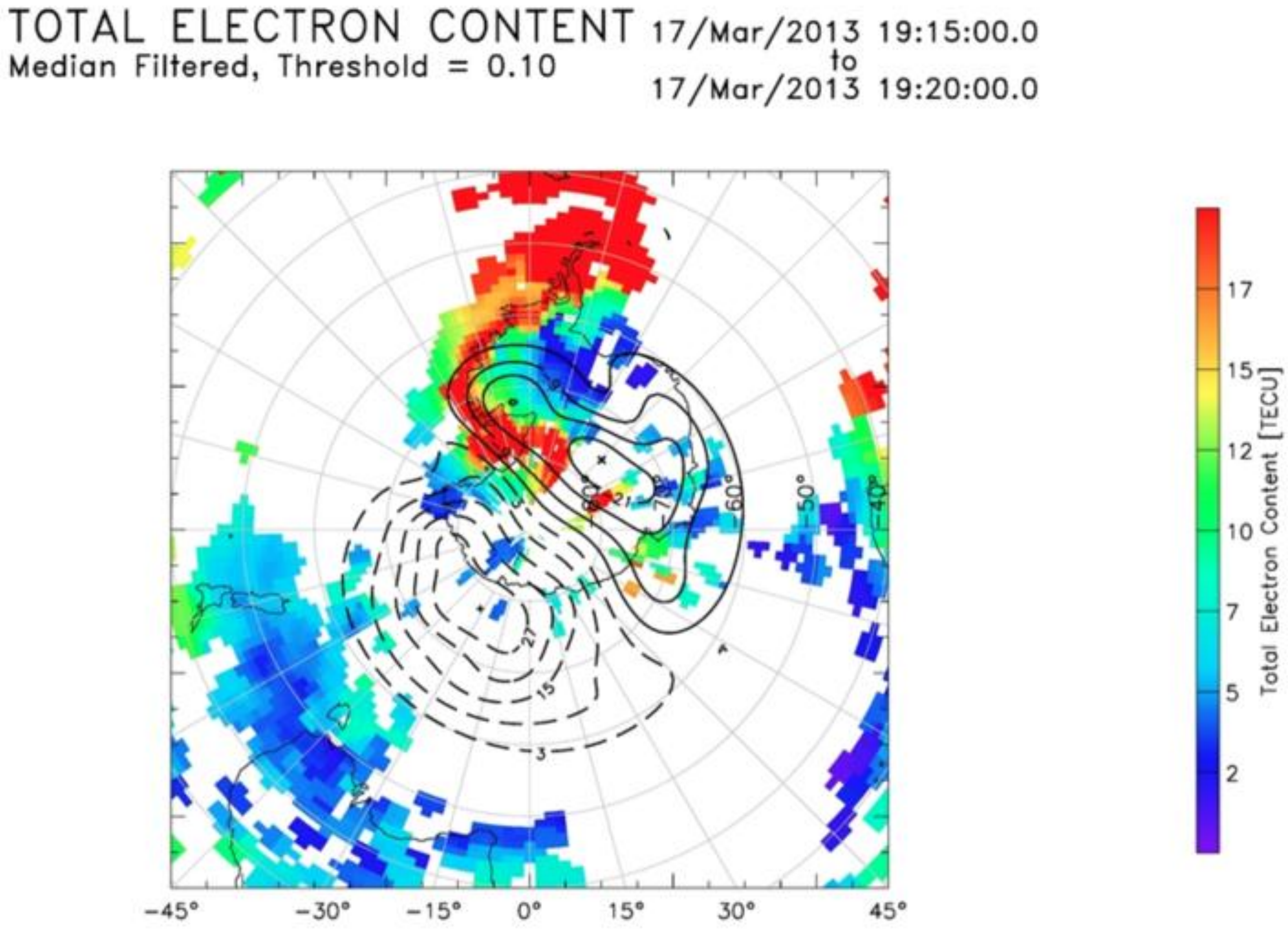


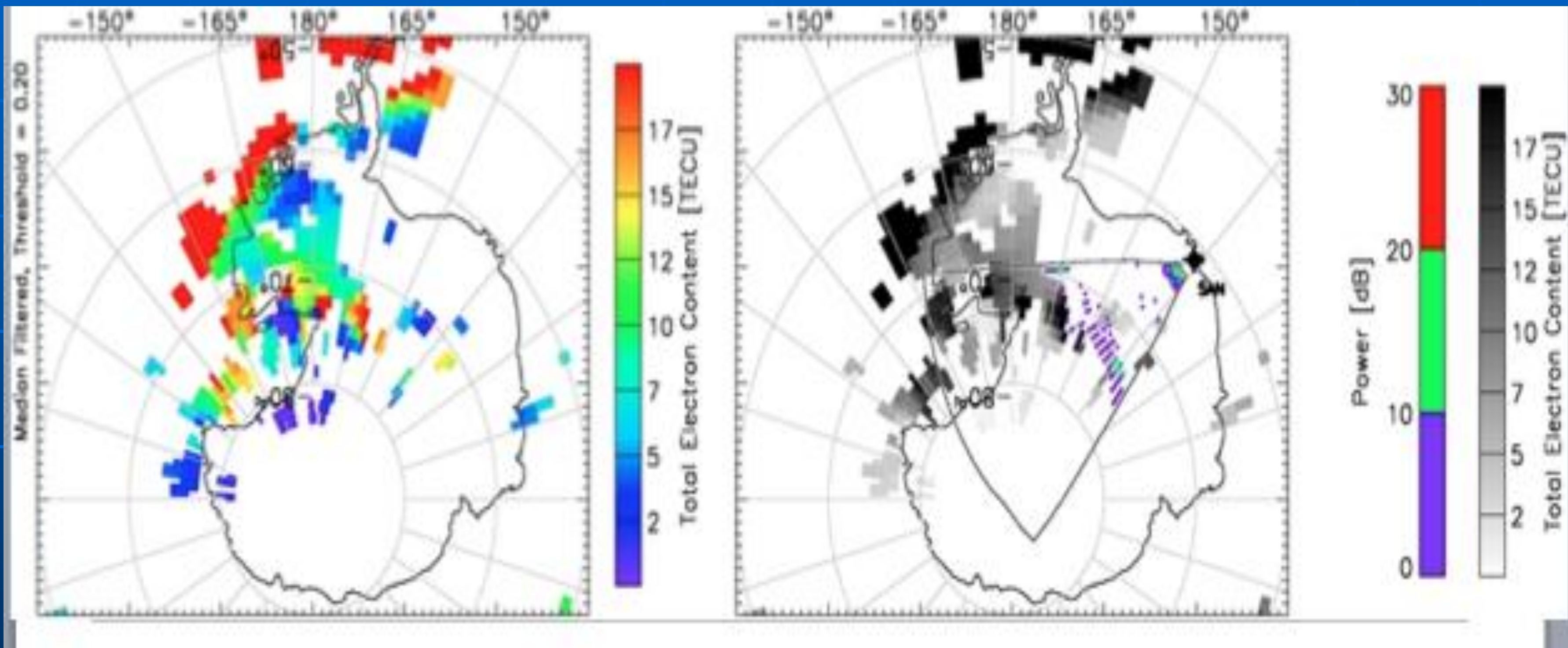
Conjugacy Examples



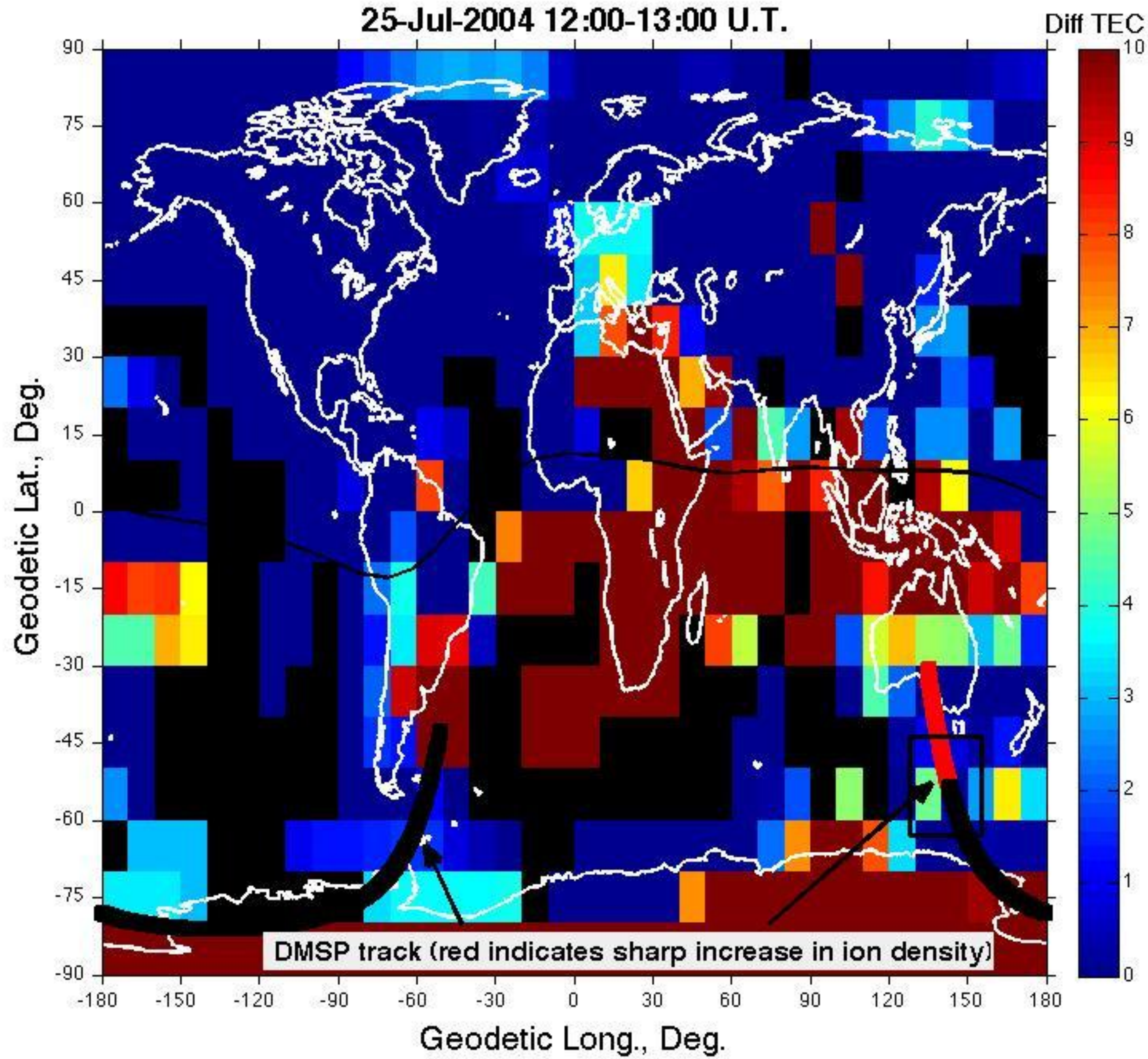


Median Filtered, Threshold = 0.20
Total Electron Content [TECU]
26
22
18
15
11
7
3
-97kV
60°
50°
40°
-45°
-30°
-15°
0°
15°
30°


TOTAL ELECTRON CONTENT 17/Mar/2013 19:15:00.0
to
17/Mar/2013 19:20:00.0
Median Filtered, Threshold = 0.10
-60°
-50°
-40°
-45°
-30°
-15°
0°
15°
30°
45°
17
15
12
10
7
5
2
Total Electron Content [TECU]

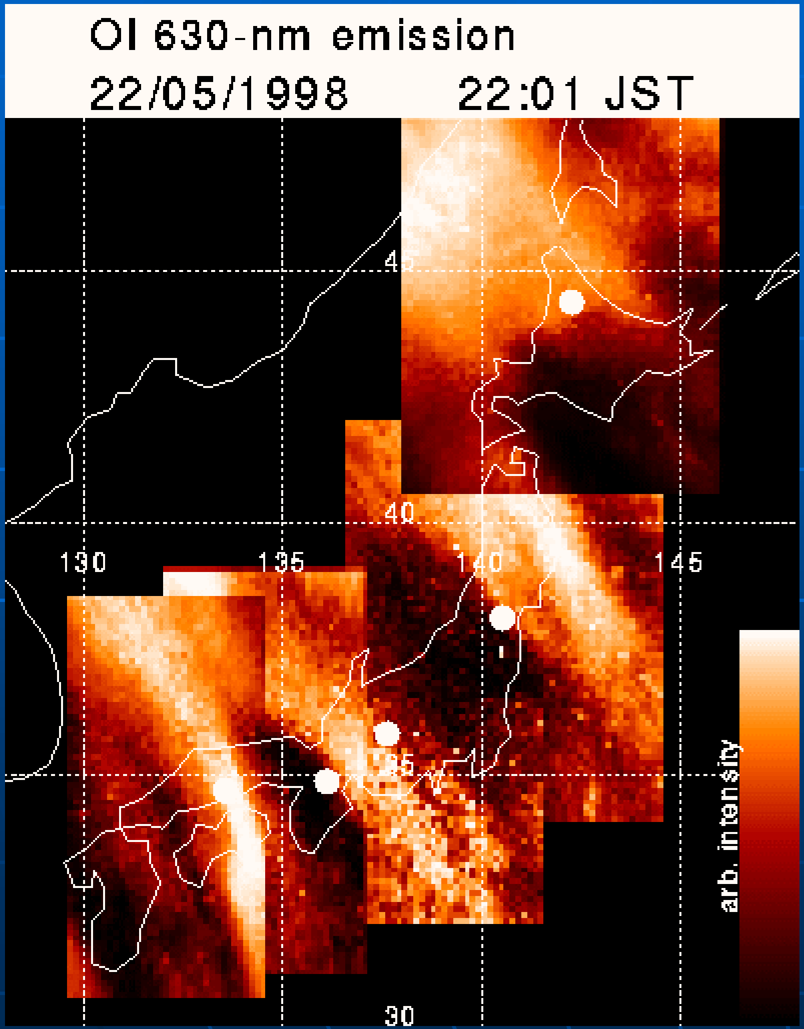


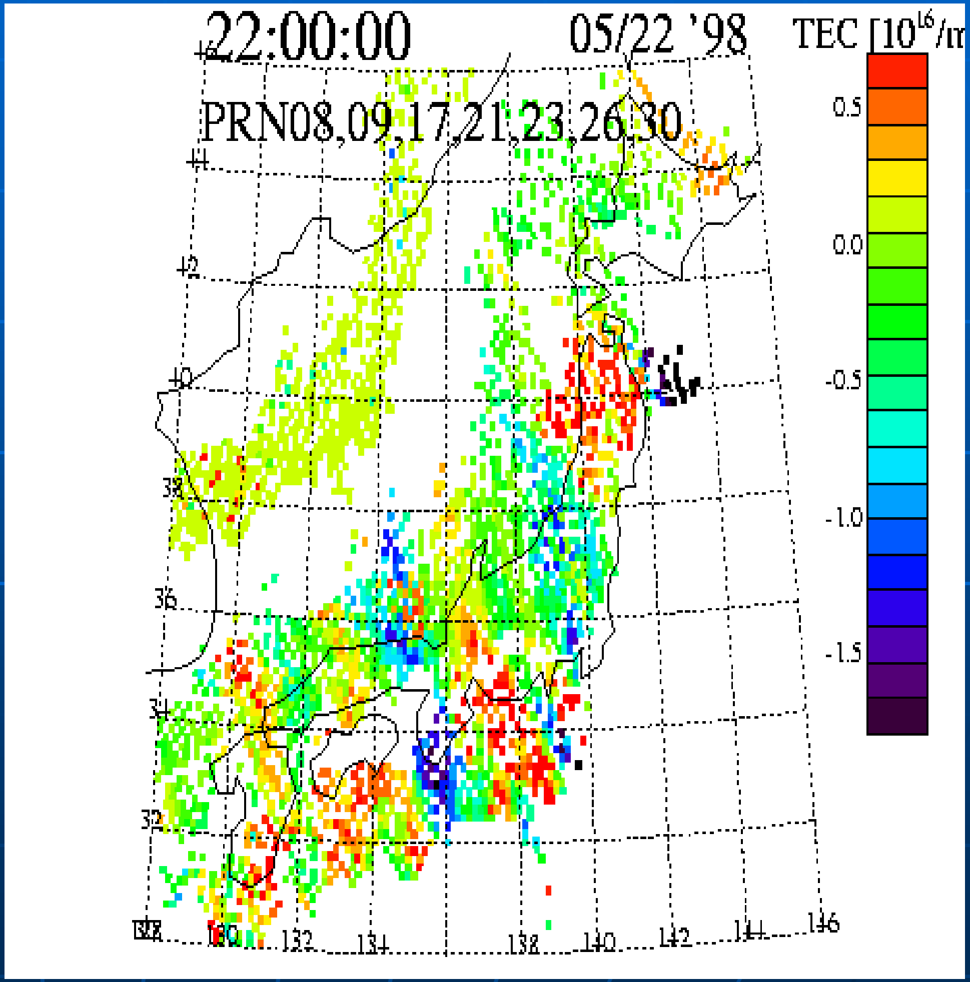
-150°
-165°
180°
165°
150°
Median Filtered, Threshold = 0.20
17
15
12
10
7
5
2
Total Electron Content [TECU]
-150°
-165°
180°
165°
150°
SAN
30
20
10
0
Power [dB]
17
15
12
10
7
5
2
Total Electron Content [TECU]

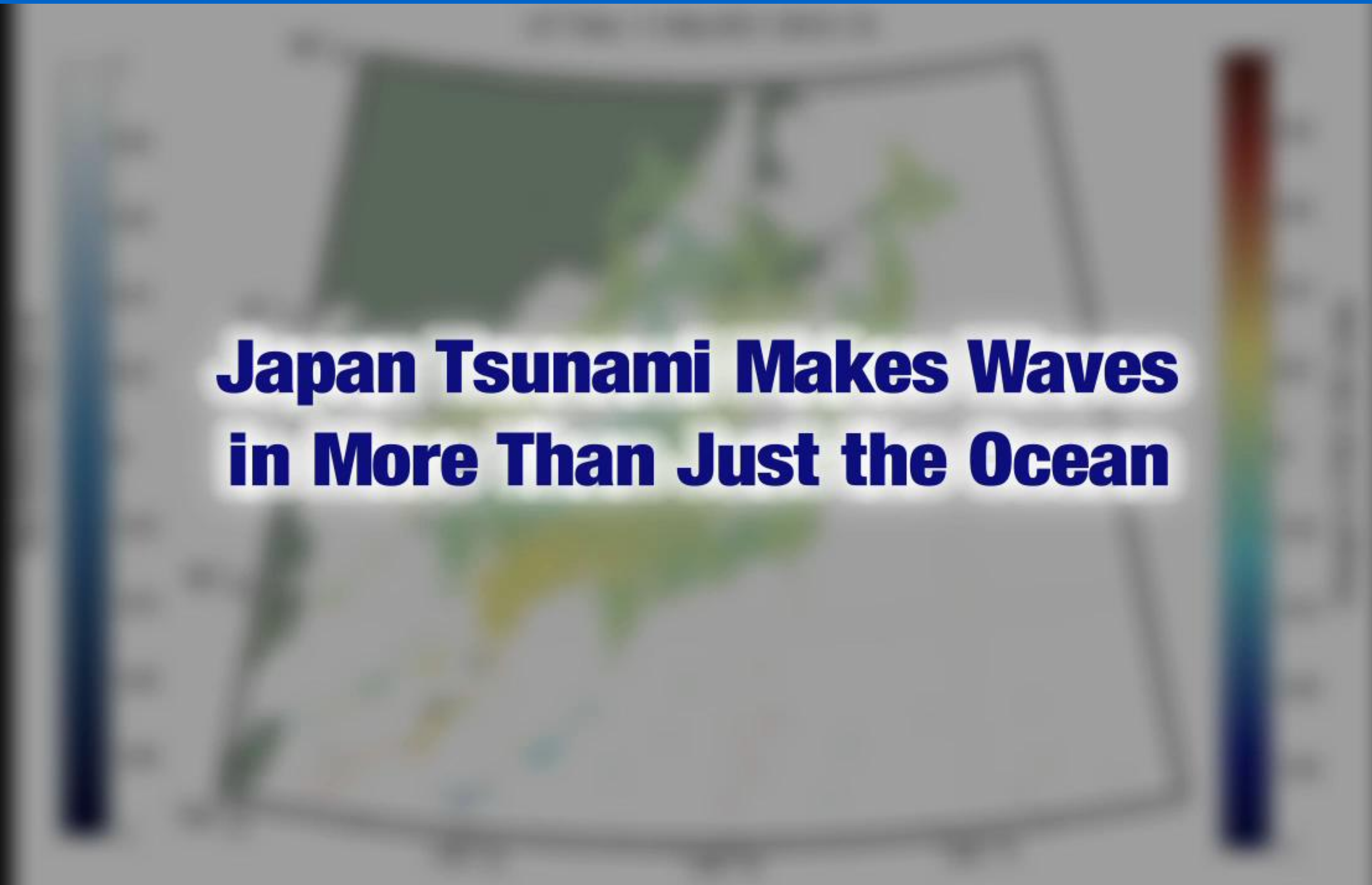


25-Jul-2004 12:00-13:00 U.T.
Diff TEC
Geodetic Lat., Deg.
Geodetic Long., Deg.
DMSP track (red indicates sharp increase in ion density)

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

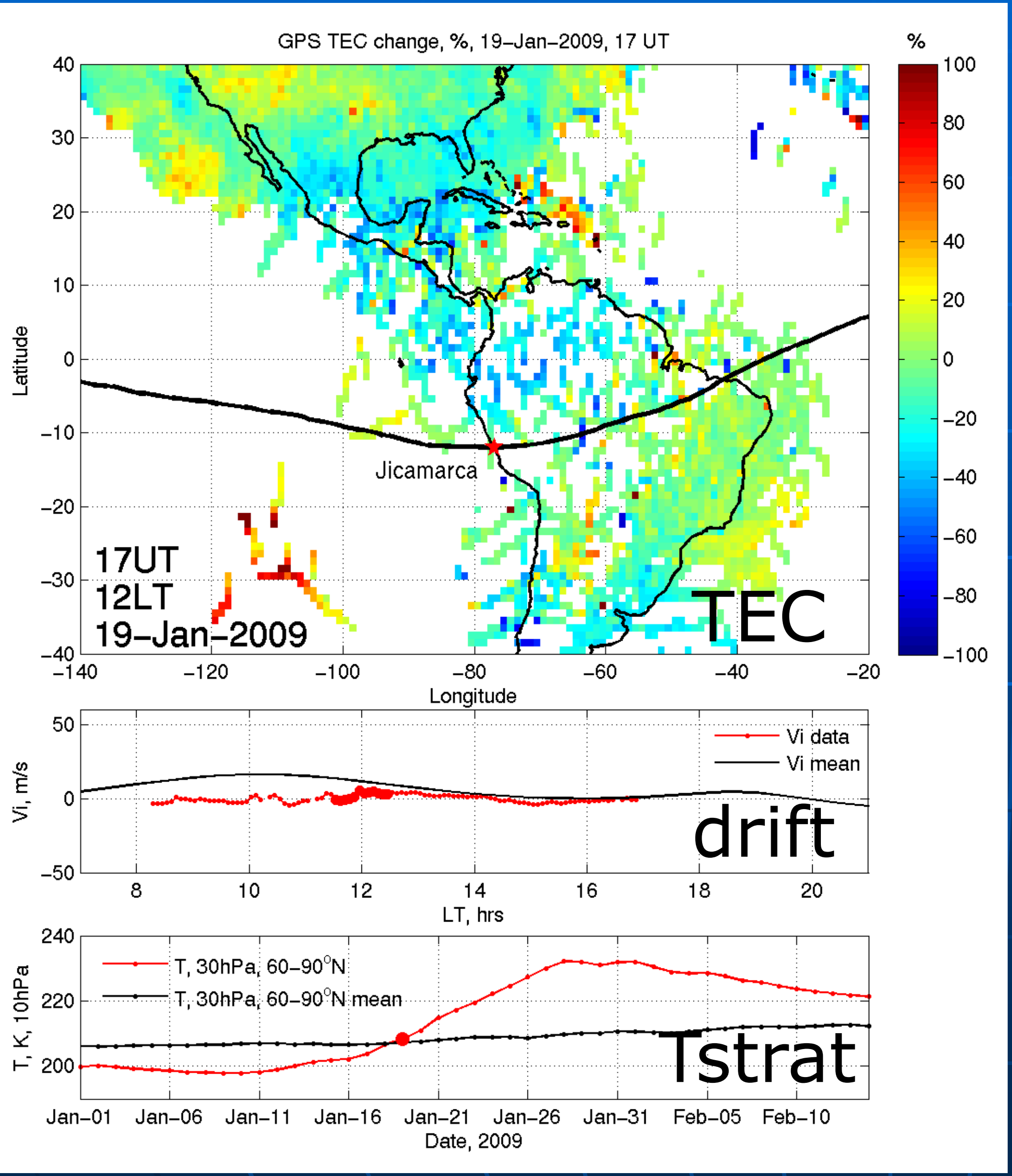






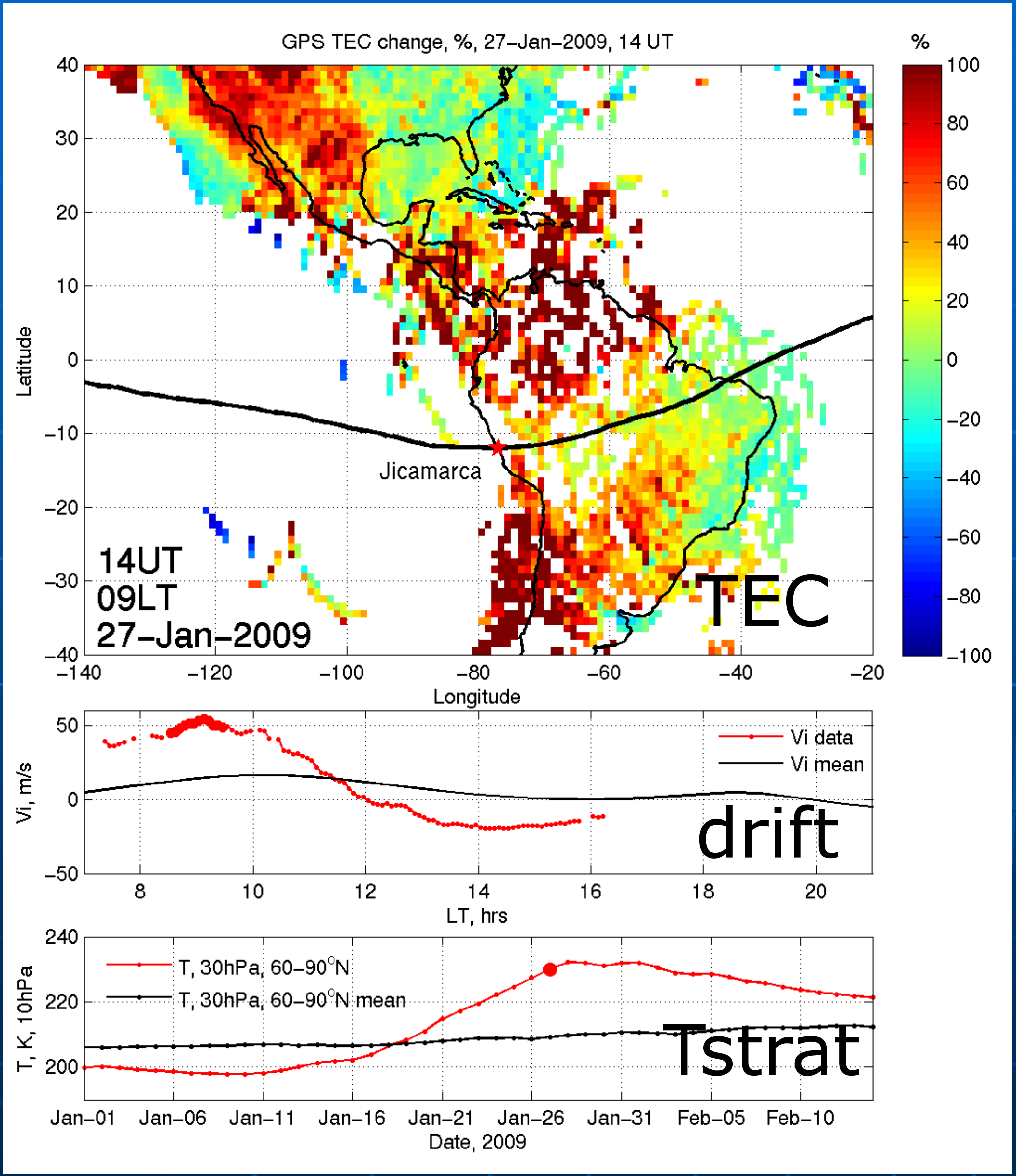
Japan Tsunami Makes Waves in More Than Just the Ocean

GPS TEC change – no warming



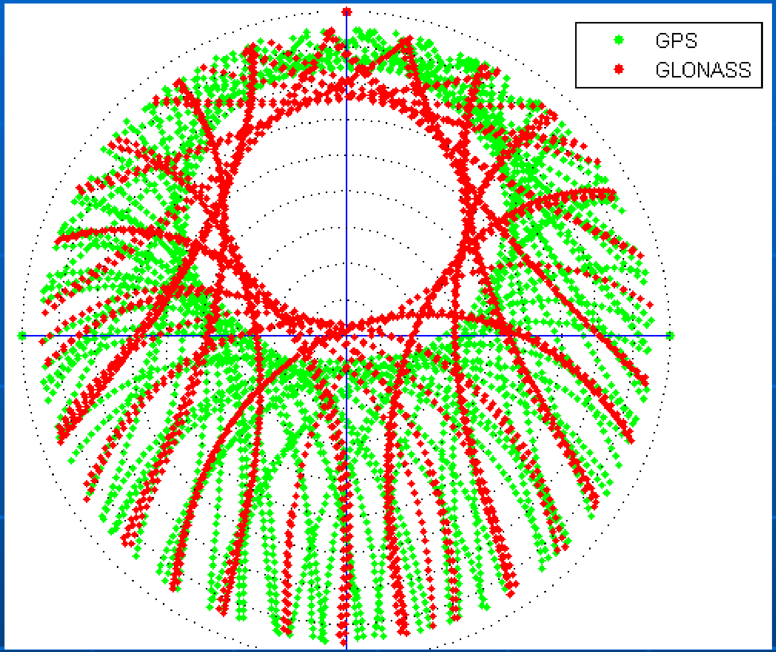
- GPS TEC (Total Electron Content) data show large-scale picture of ionospheric behavior
- Before the warming, TEC change is 10-20% from mean and vertical drift is small
- The mean is Jan 1-14, 2009

GPS TEC during warming: morning sector

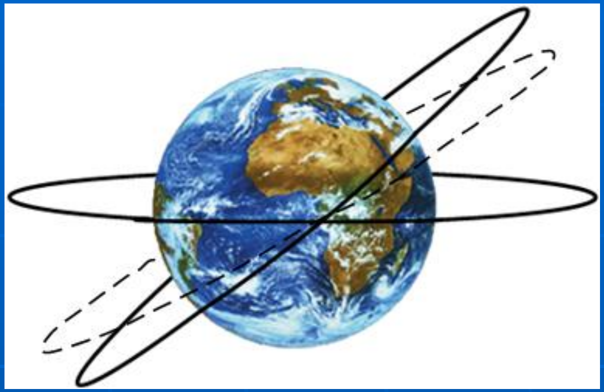


- During stratwarming, TEC increases in excess of 50-100% in the morning
- Large upward drift at Jicamarca
- The magnitude of increase is similar to effects of severe geomagnetic storms

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



GLONASS orbit plane inclination: 65º



COMPASS

GALILEO

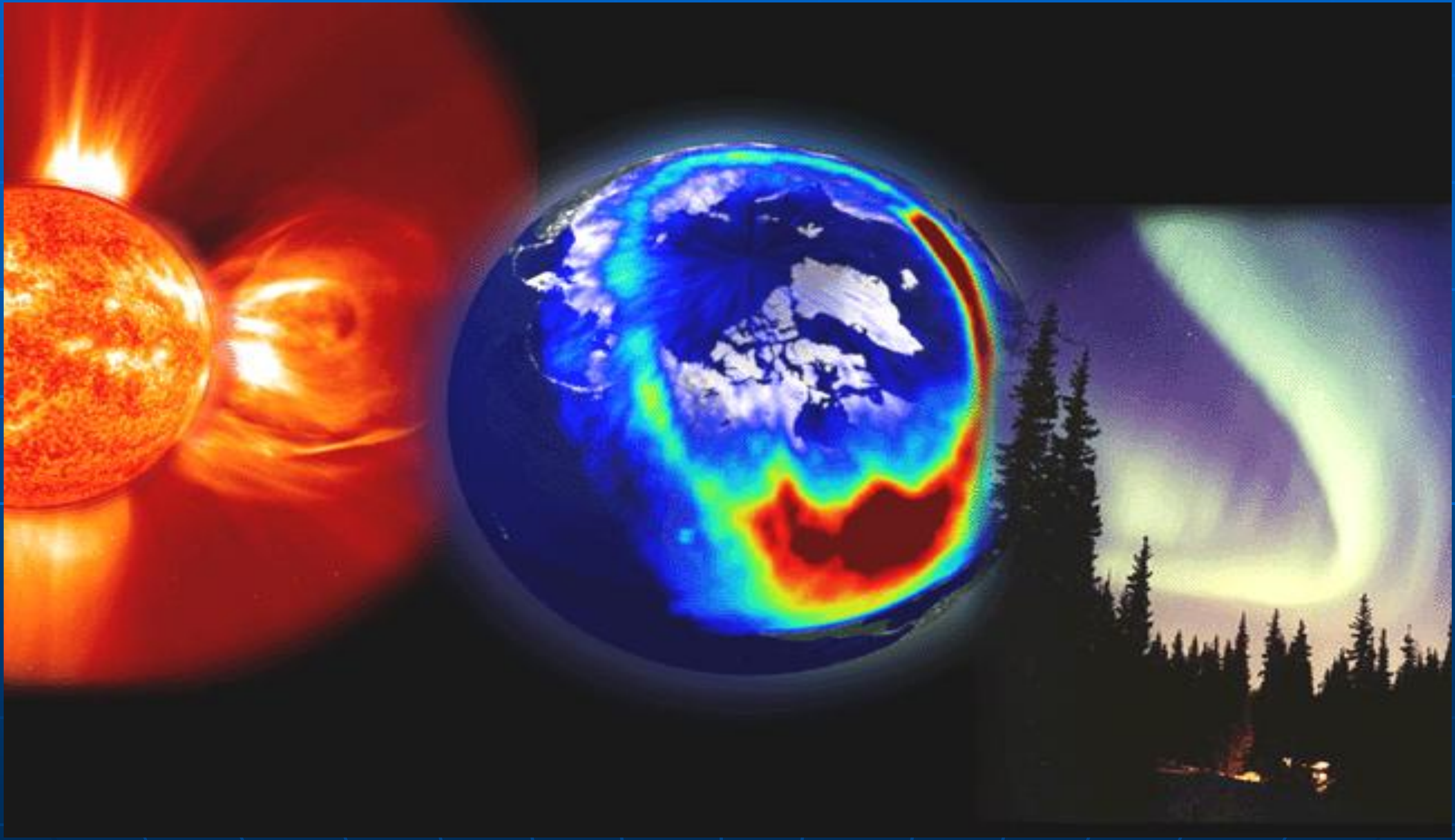
SUMMARY

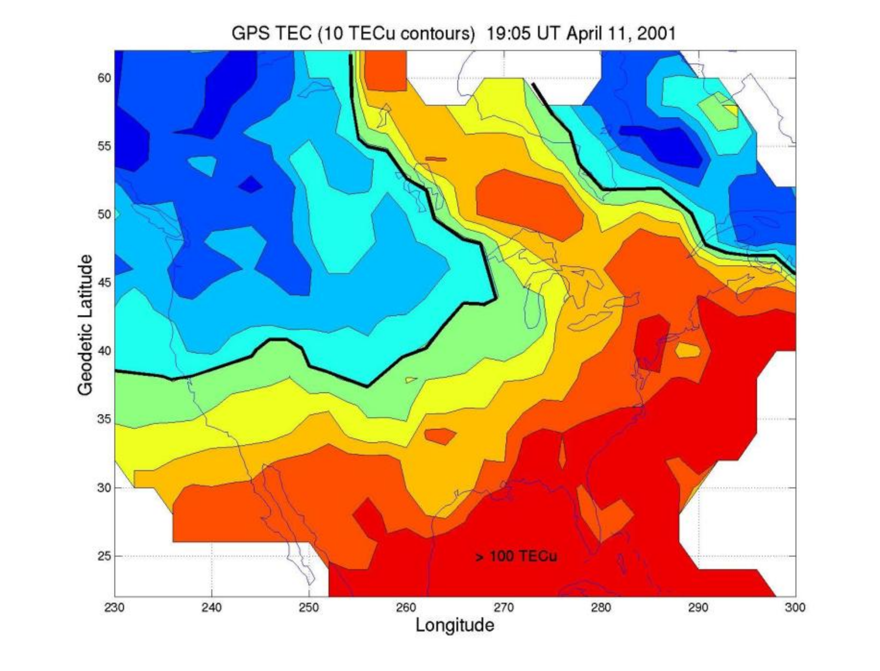
Over the last 10 years, global GPS TEC maps have provided a paradigm shift in the way we study the ionosphere/plasmasphere/magnetosphere.

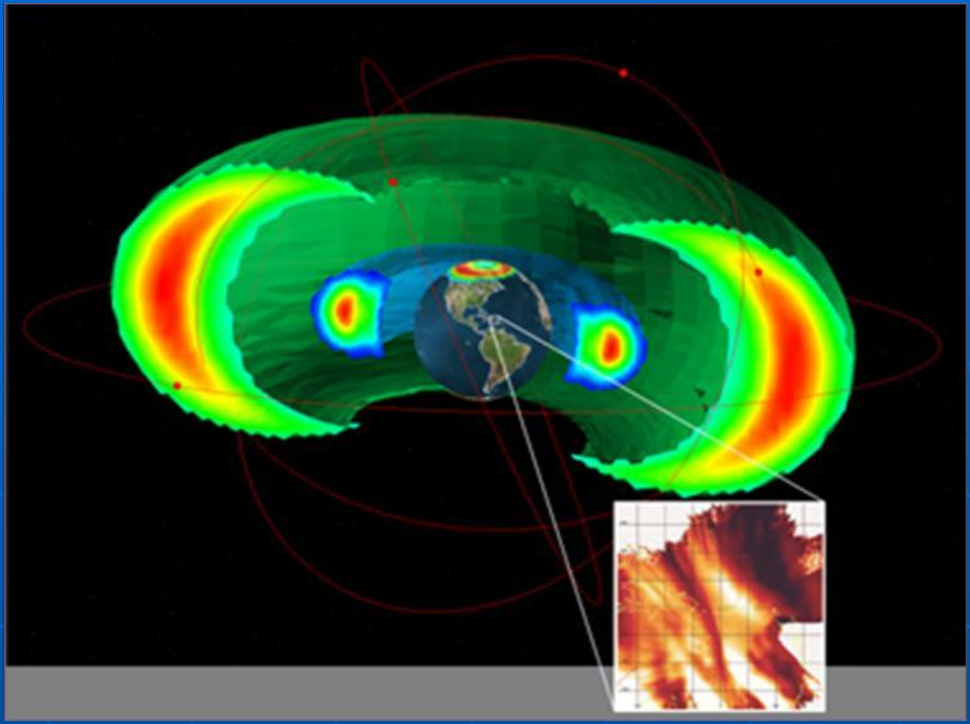
GPS has played a key role in system science studies of the atmosphere, but I think we are only at the beginning. How we combine GNSS observations with other data sets is the key to the future.

New discoveries are there buried in the data.

From the Sun to the Earth







Magnetosphere Ionosphere Atmosphere Coupling