The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2333-24

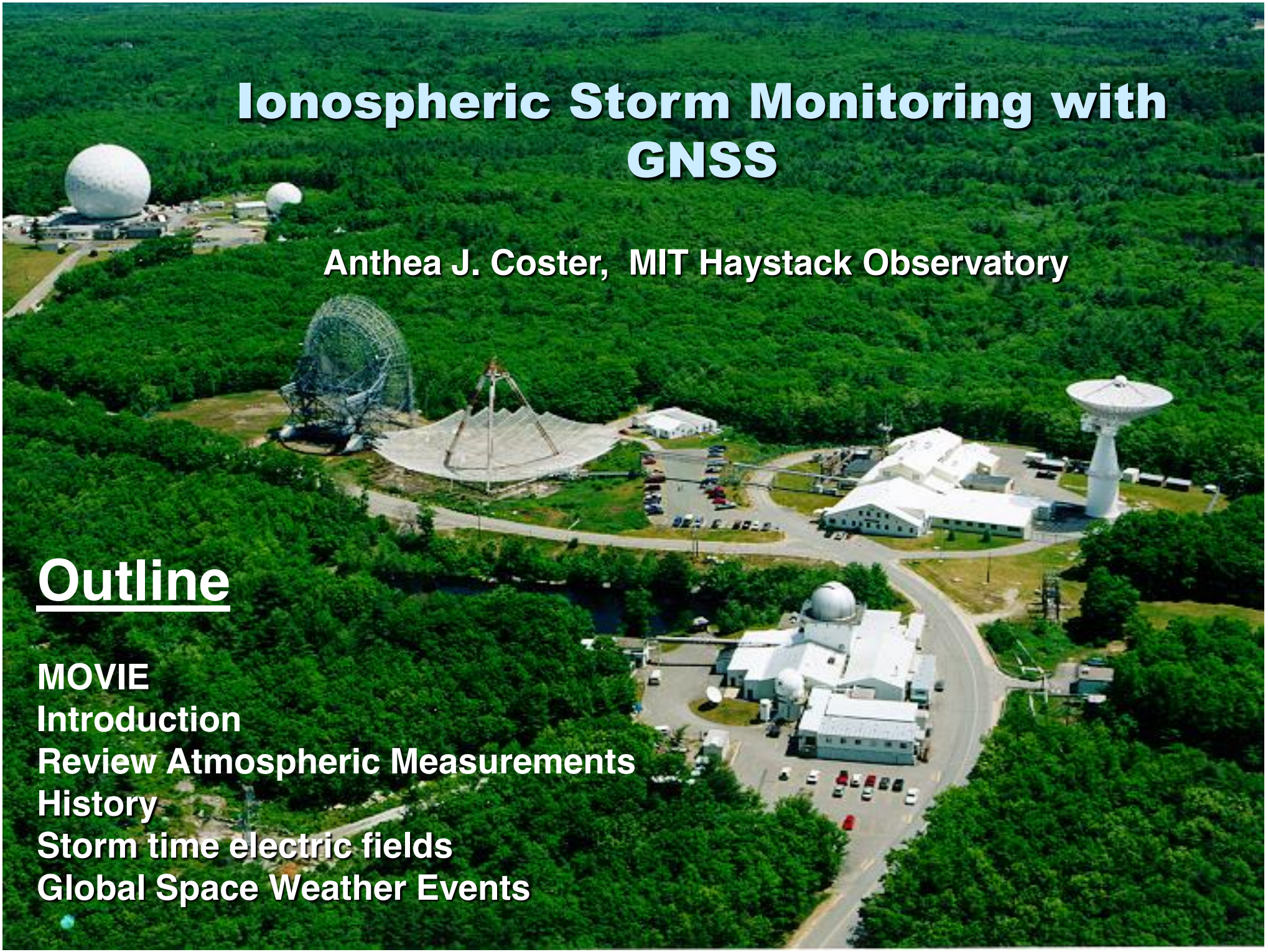
Workshop on Science Applications of GNSS in Developing Countries (11-27 April), followed by the: Seminar on Development and Use of the Ionospheric NeQuick Model (30 April-1 May)

11 April - 1 May, 2012

Ionospheric Storm Monitoring with GNSS

COSTER Anthea Jane

M.I.T. - Atmospheric Sciences Group
Haystack Observatory, Off Route 40
01886 Westford
U.S.A.



Ionospheric Storm Monitoring with GNSS

Anthea J. Coster, MIT Haystack Observatory

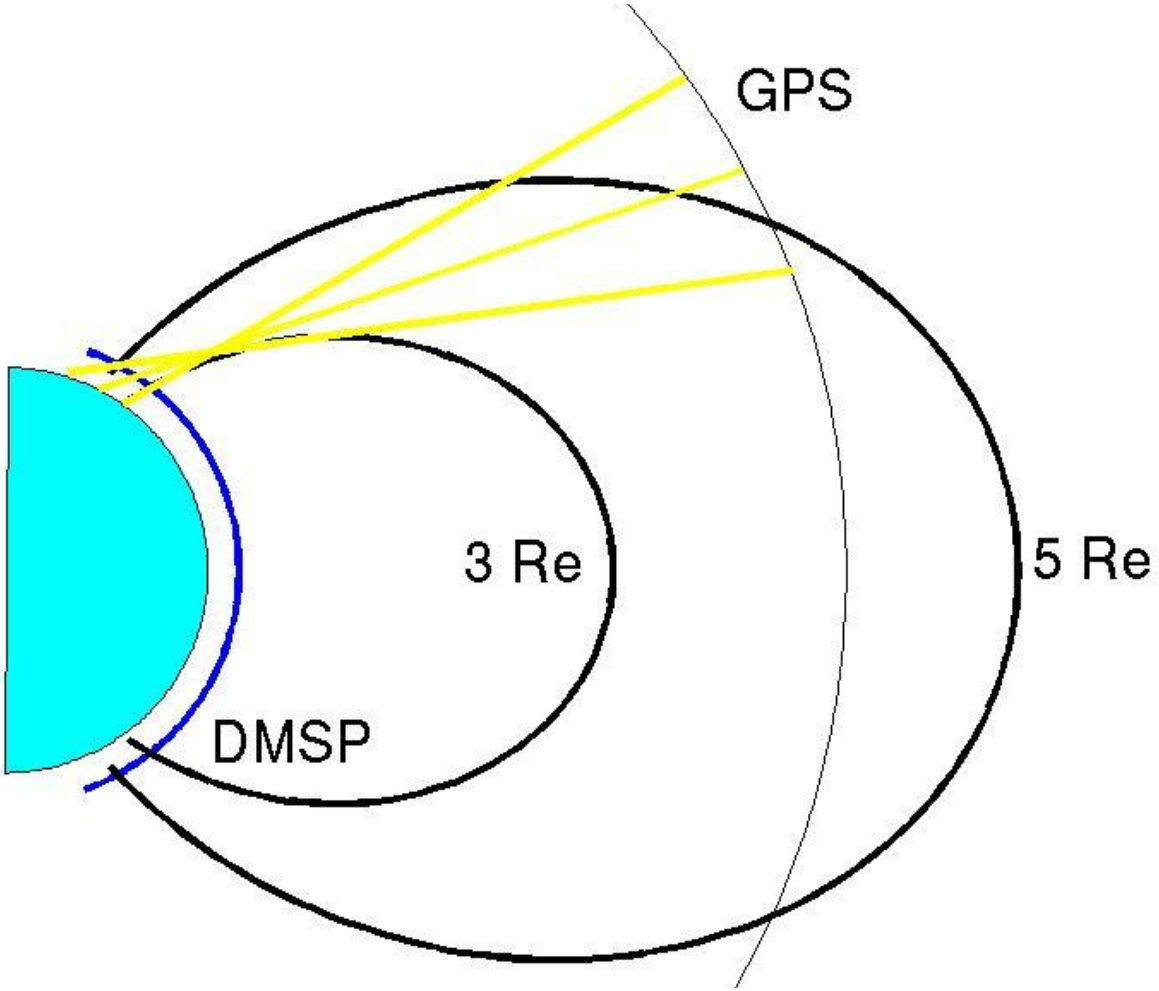
Outline

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

Definition:

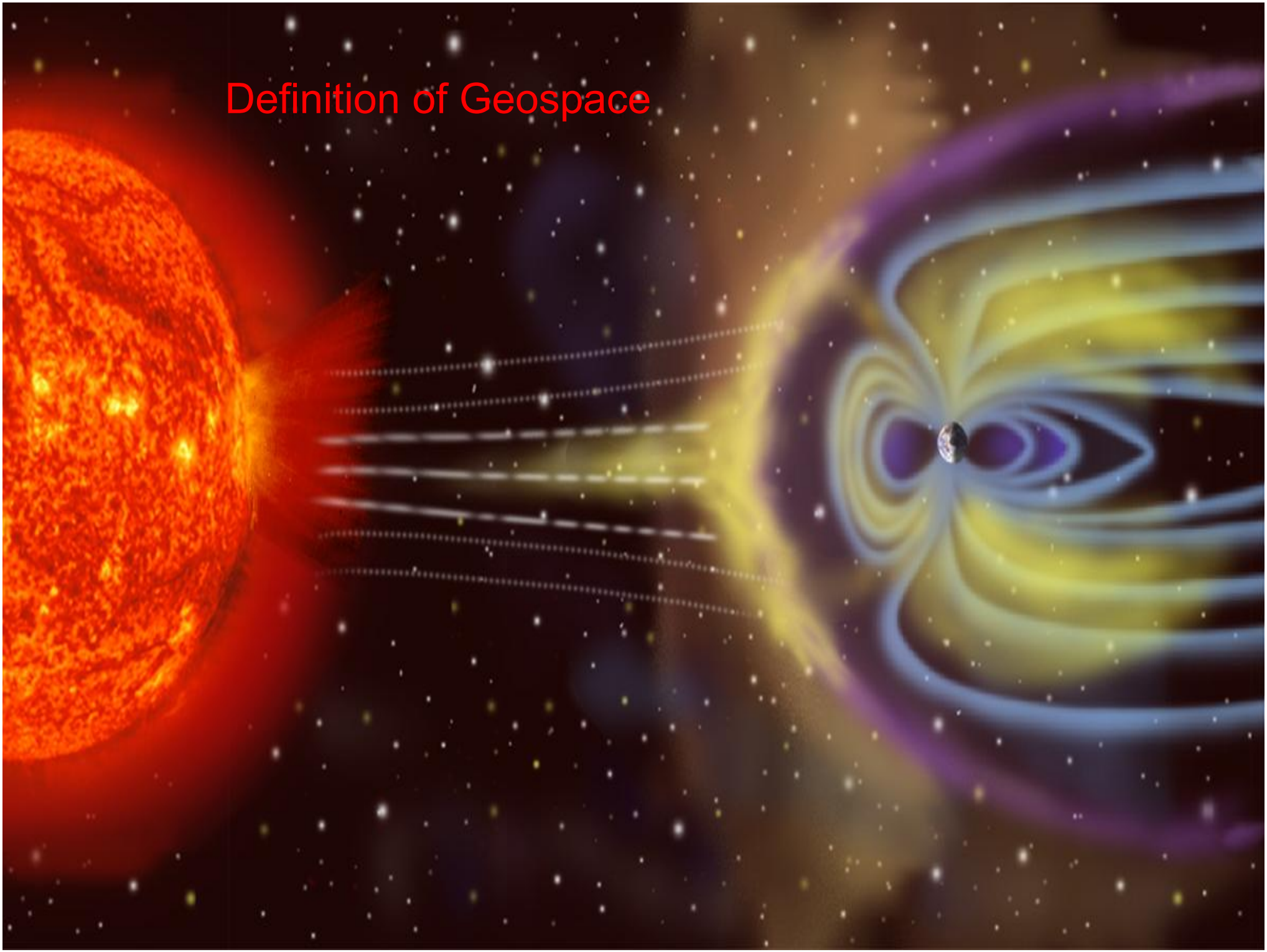
TEC = Total Electron Content (10^{16} x el/$m^{2)}$

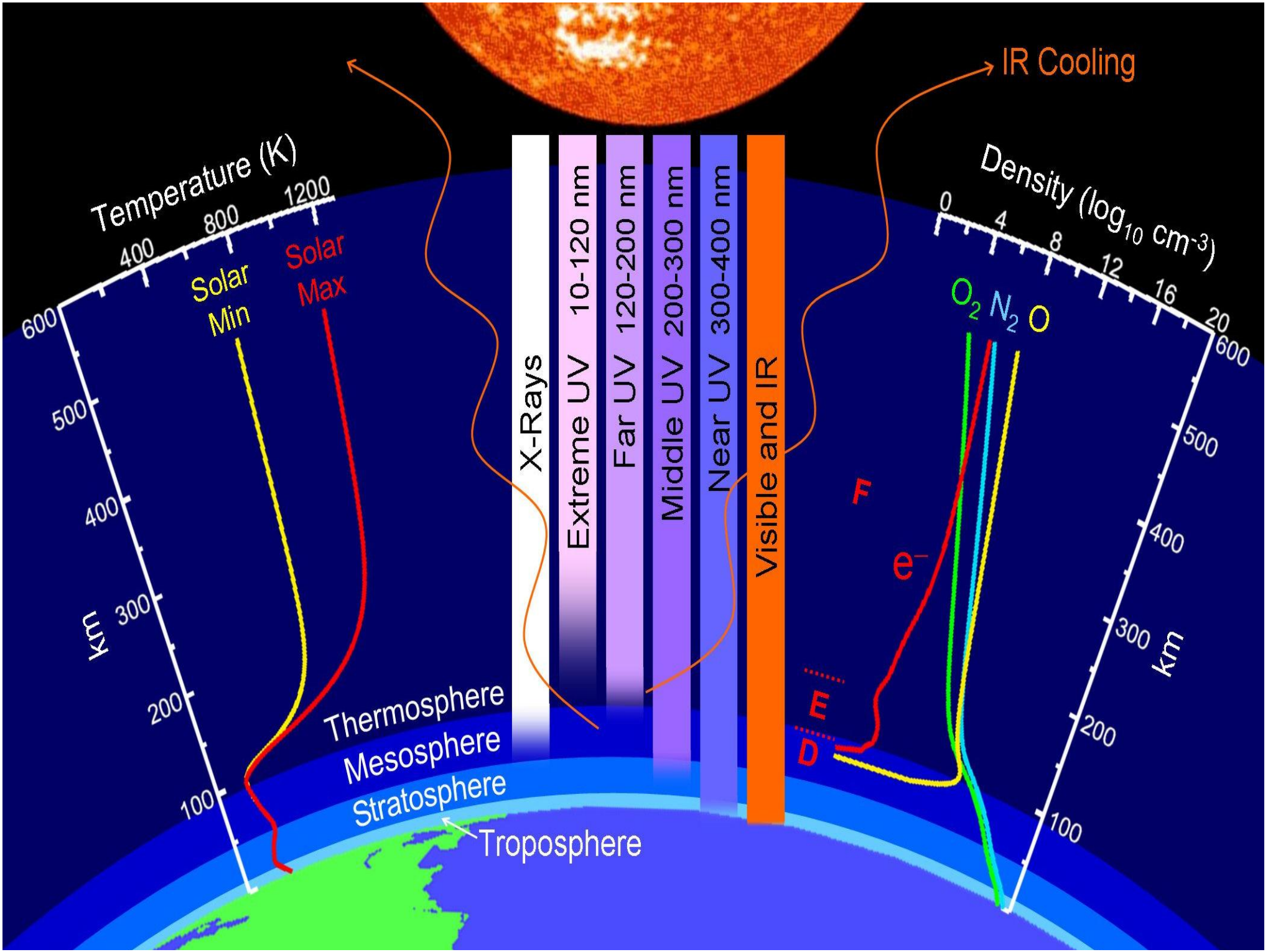
GPS samples the ionosphere and plasmasphere to an altitude of ~20,000 km



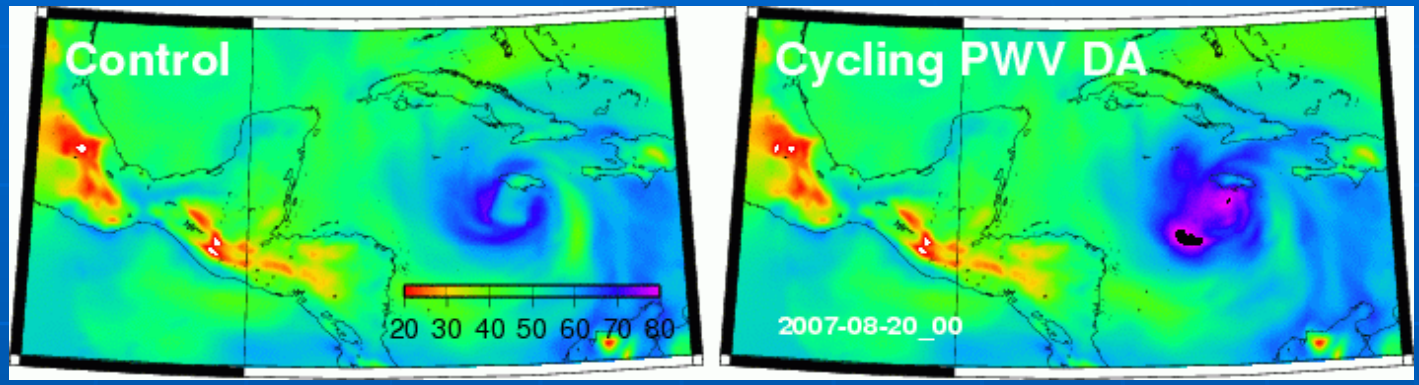
TEC is a measure of integrated density in a 1 m^2 column

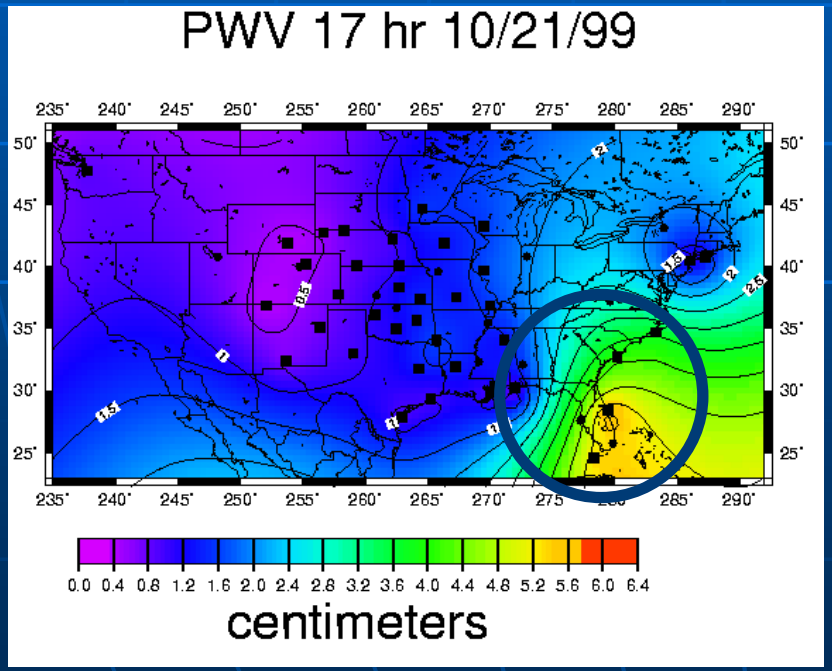
1 TEC unit = 10^{16} electrons m^{-2}

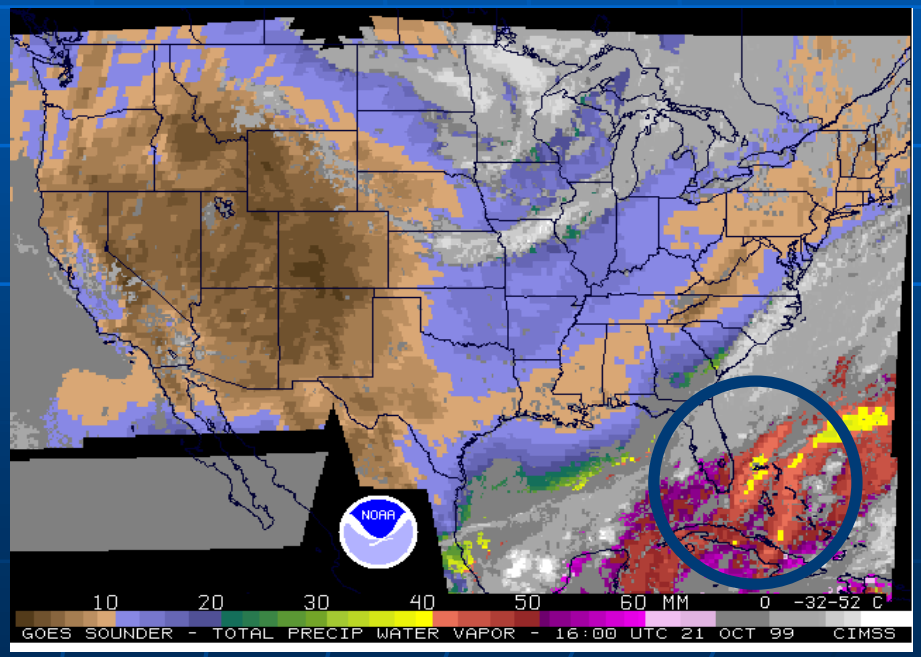

Definition of Geospace


IR Cooling
Temperature (K)
400
800
1200
Solar Min
Solar Max
600
500
400
300
200
100
km
X-Rays
Extreme UV 10-120 nm
Far UV 120-200 nm
Middle UV 200-300 nm
Near UV 300-400 nm
Visible and IR
Thermosphere
Mesosphere
Stratosphere
Troposphere
Density (log_{10} cm^{-3})
0
4
8
12
16
20
O_2 N_2 O
F
e^-
E
D
600
500
400
300
200
100
km

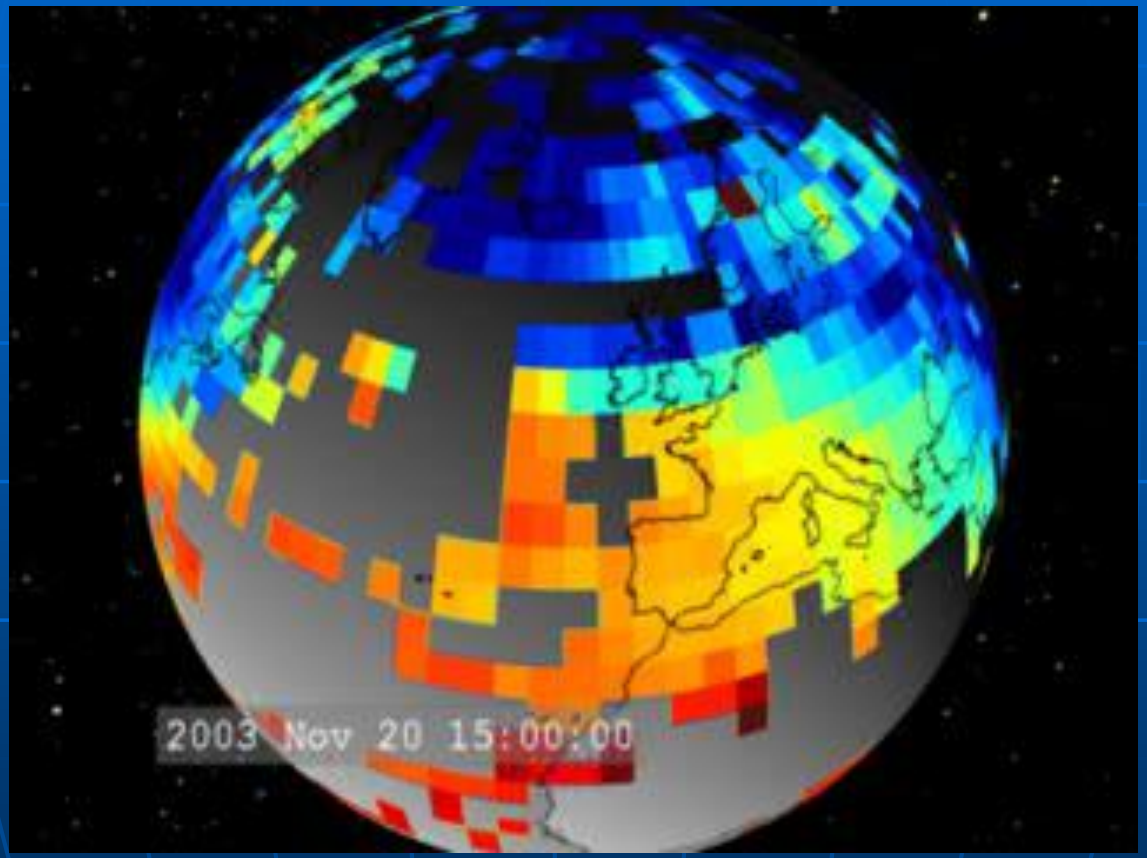
Definition of Space Weather: Analogy with Weather



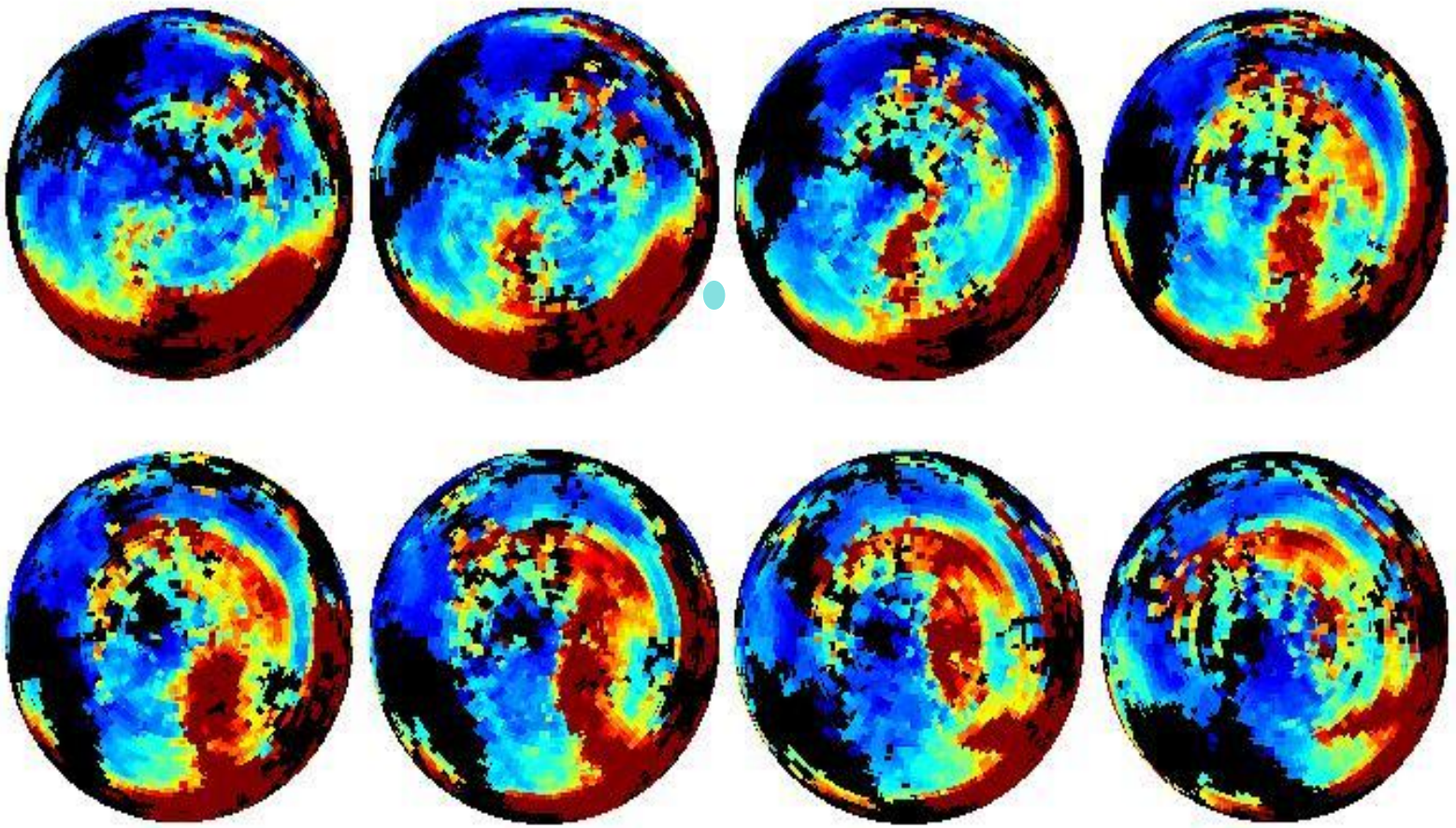




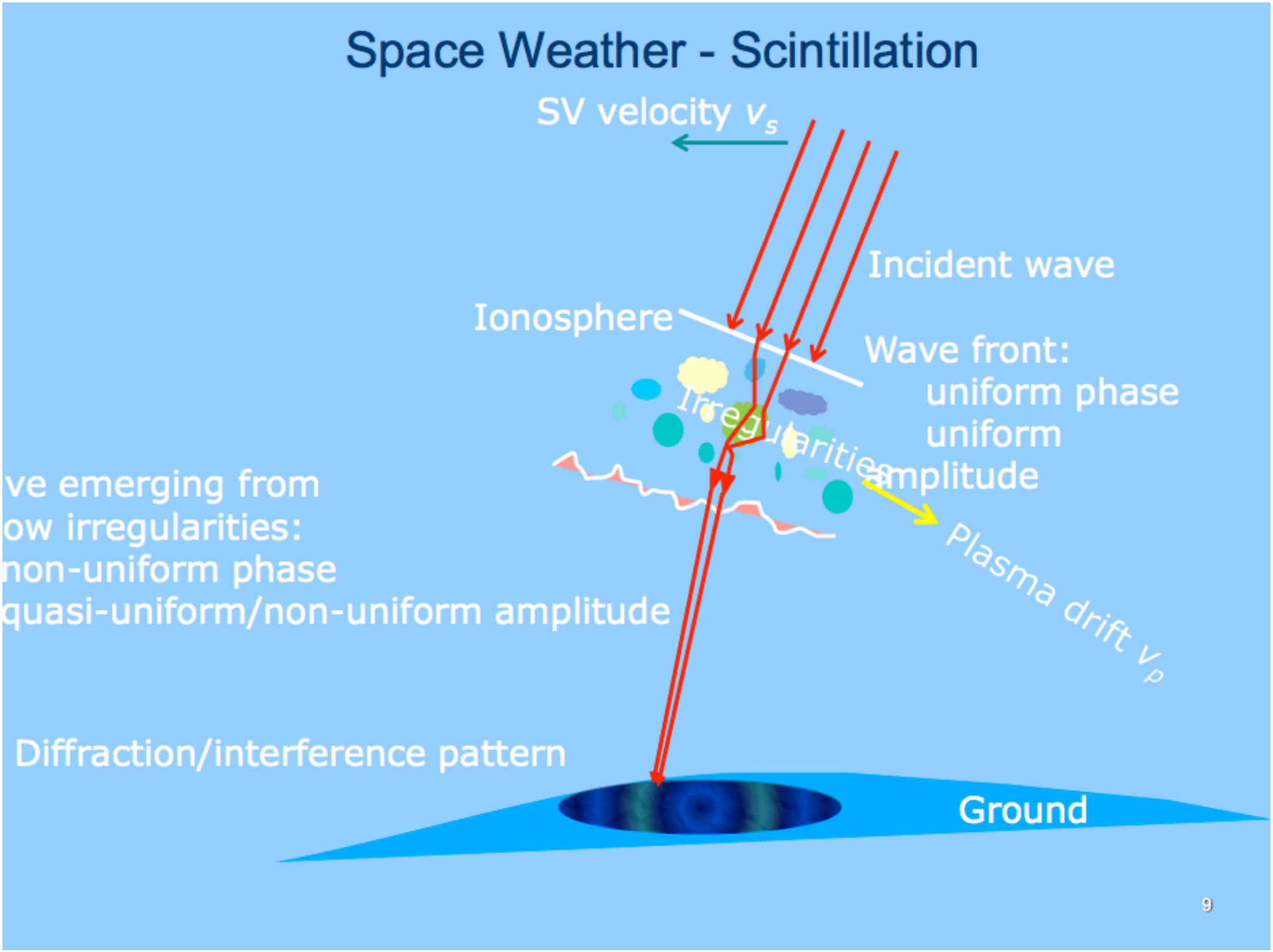
Space Weather



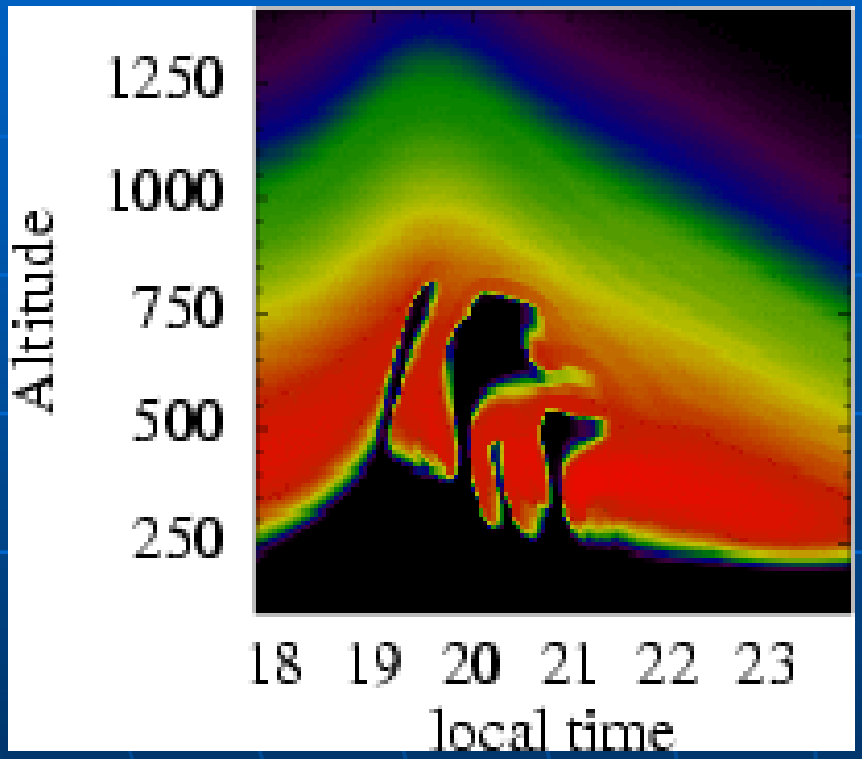
Space Weather

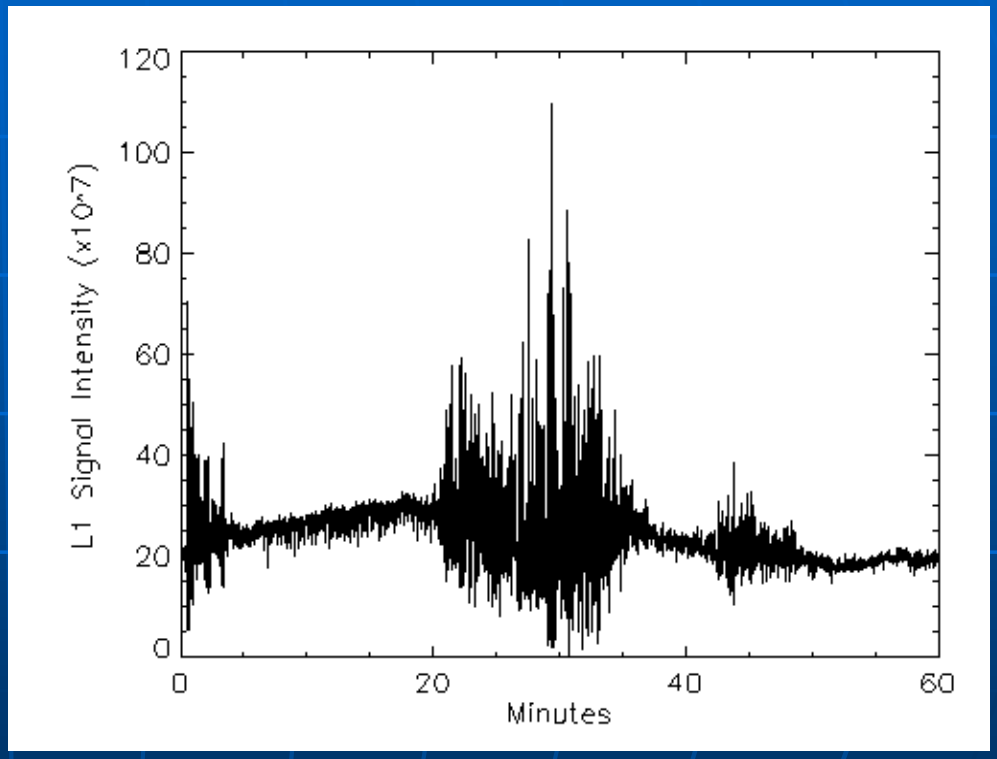


Space Weather - Scintillation



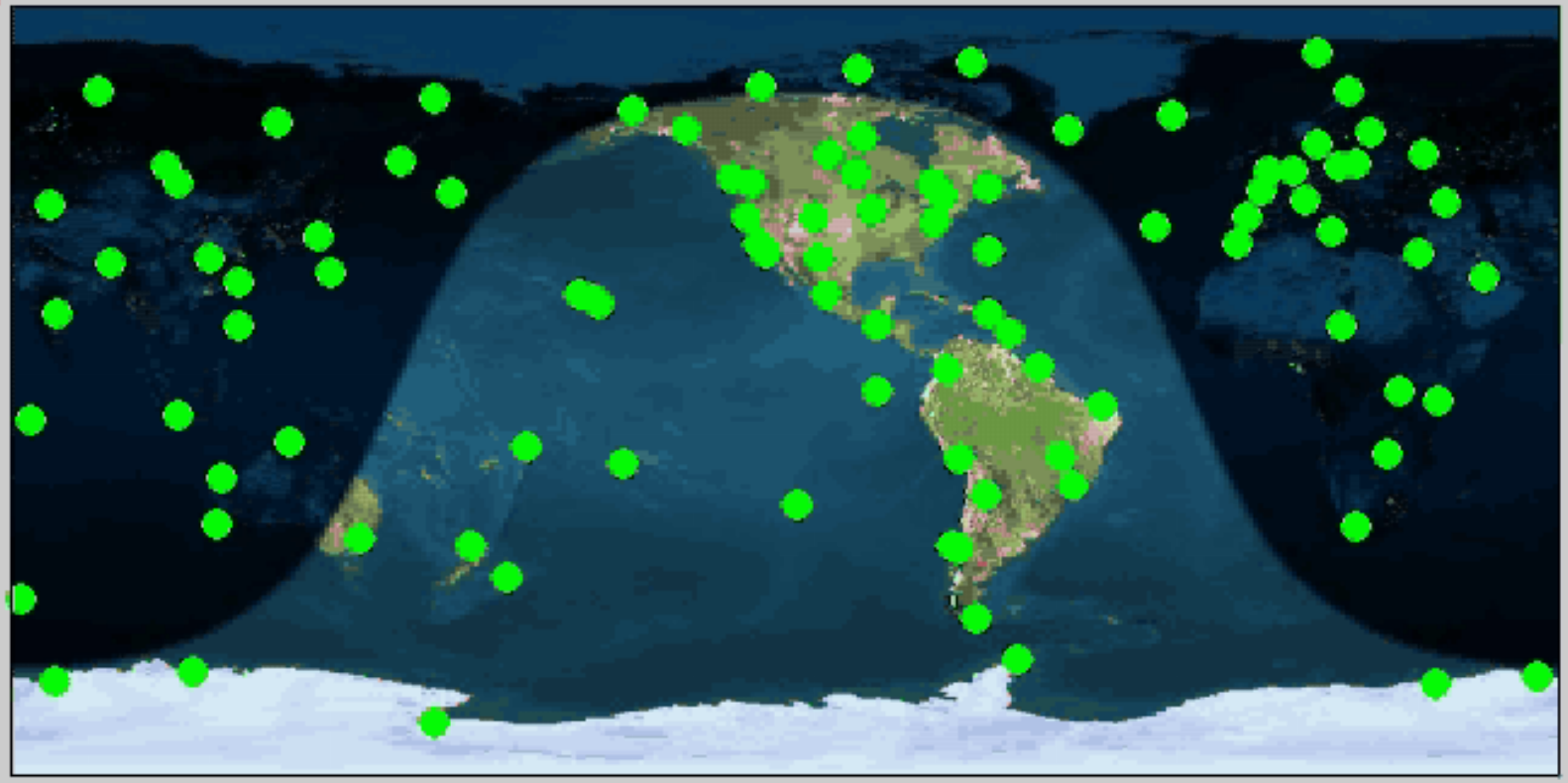
Space Weather - Scintillation





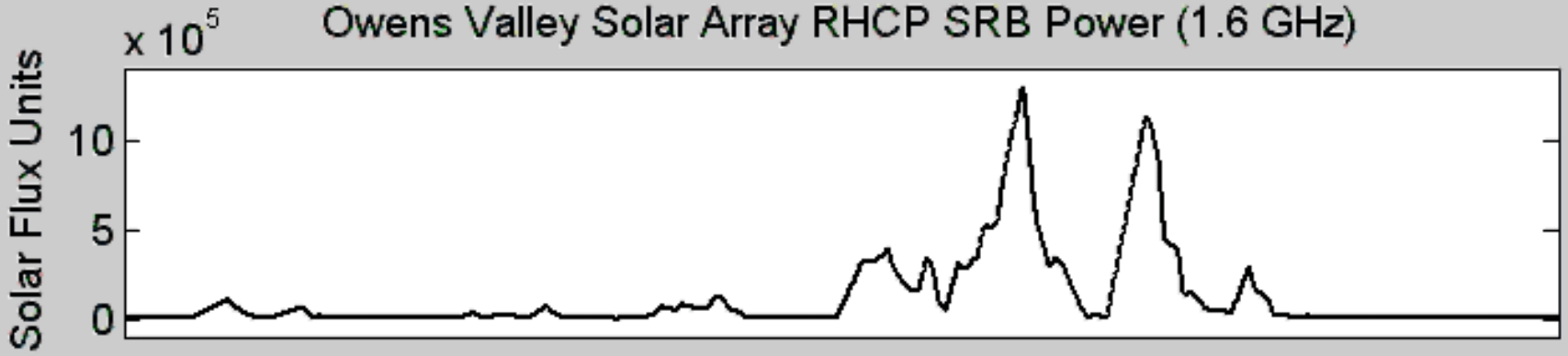
Cornell University

IGS Network, 6 December 2006

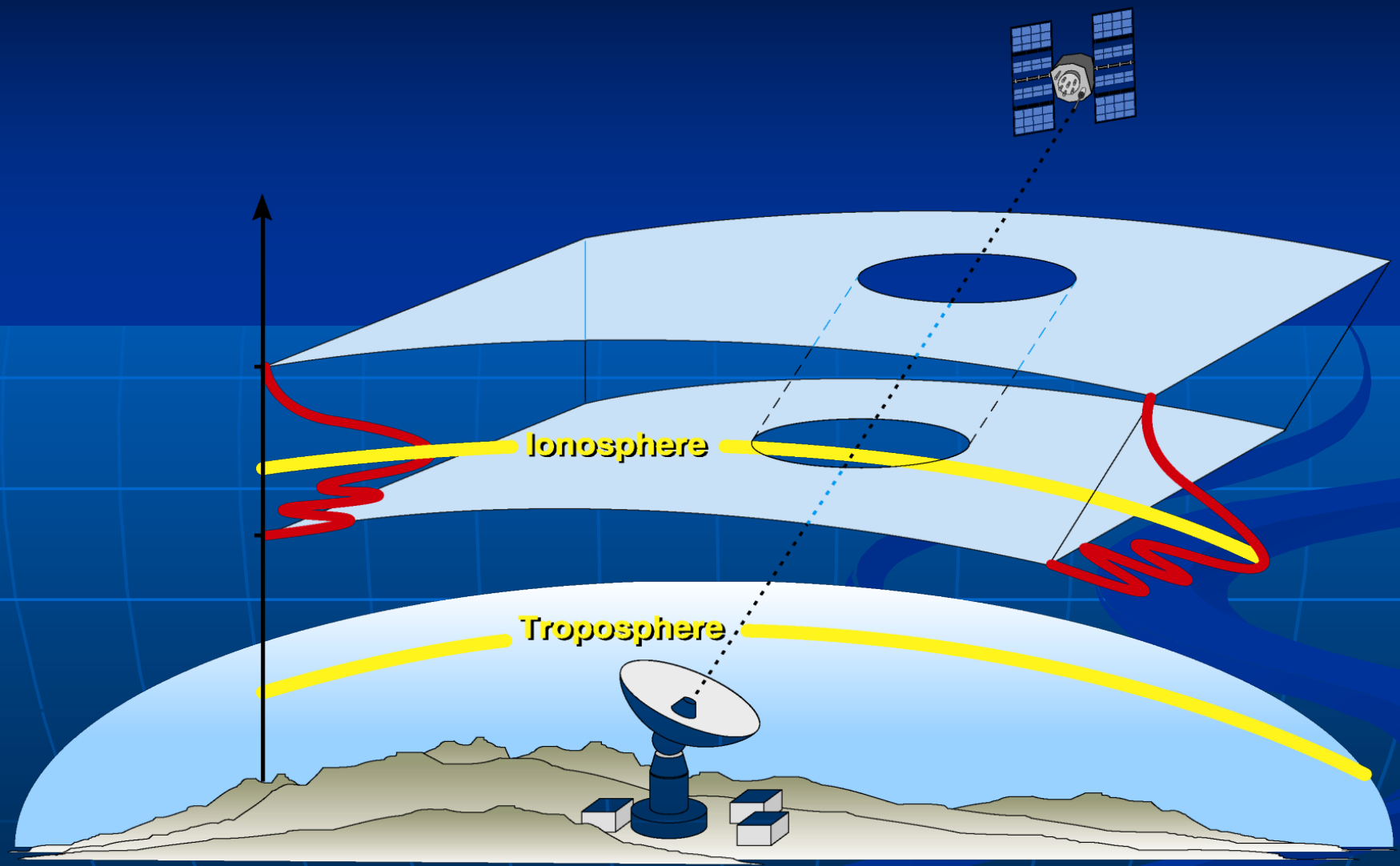


19:14:46 UTC

Failure Operational



Atmospheric Propagation



From Attila Komjathy, JPL

Outline

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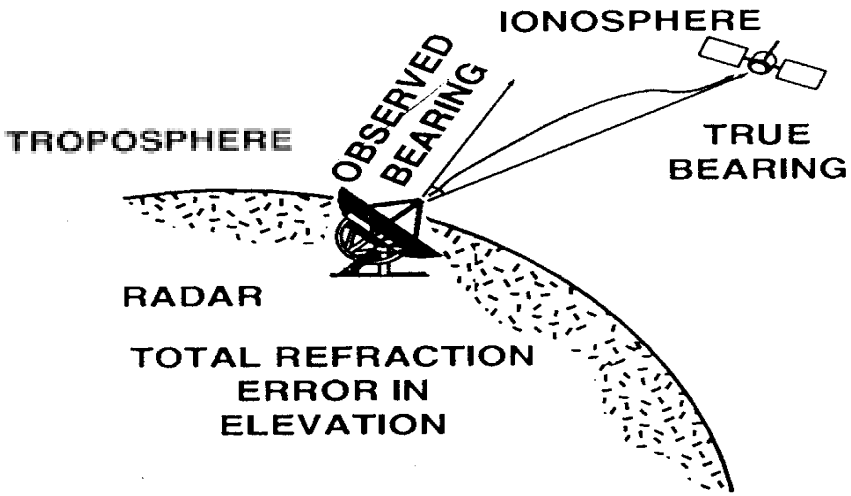
Review Atmospheric Measurements

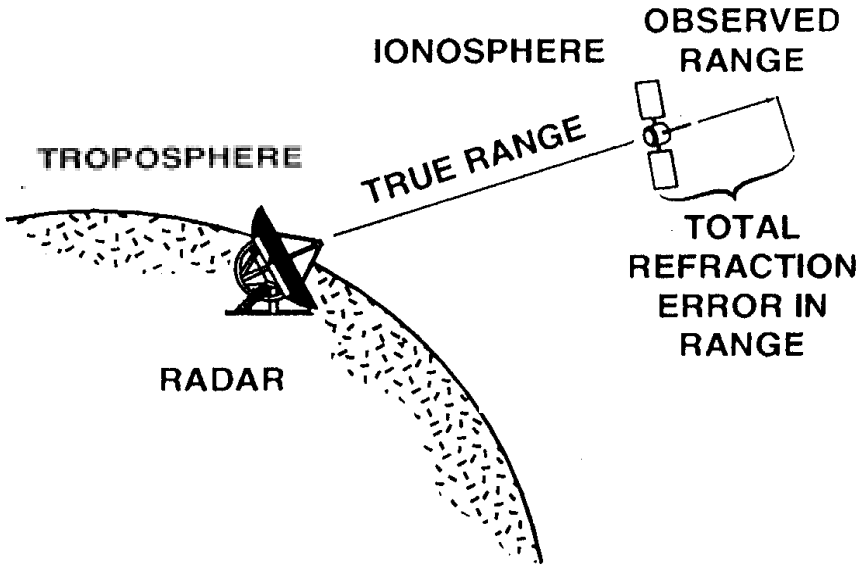
History

Storm time electric fields

Global Space Weather Events

Illustration of Atmospheric Effects





Ionospheric Range Correction

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

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

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

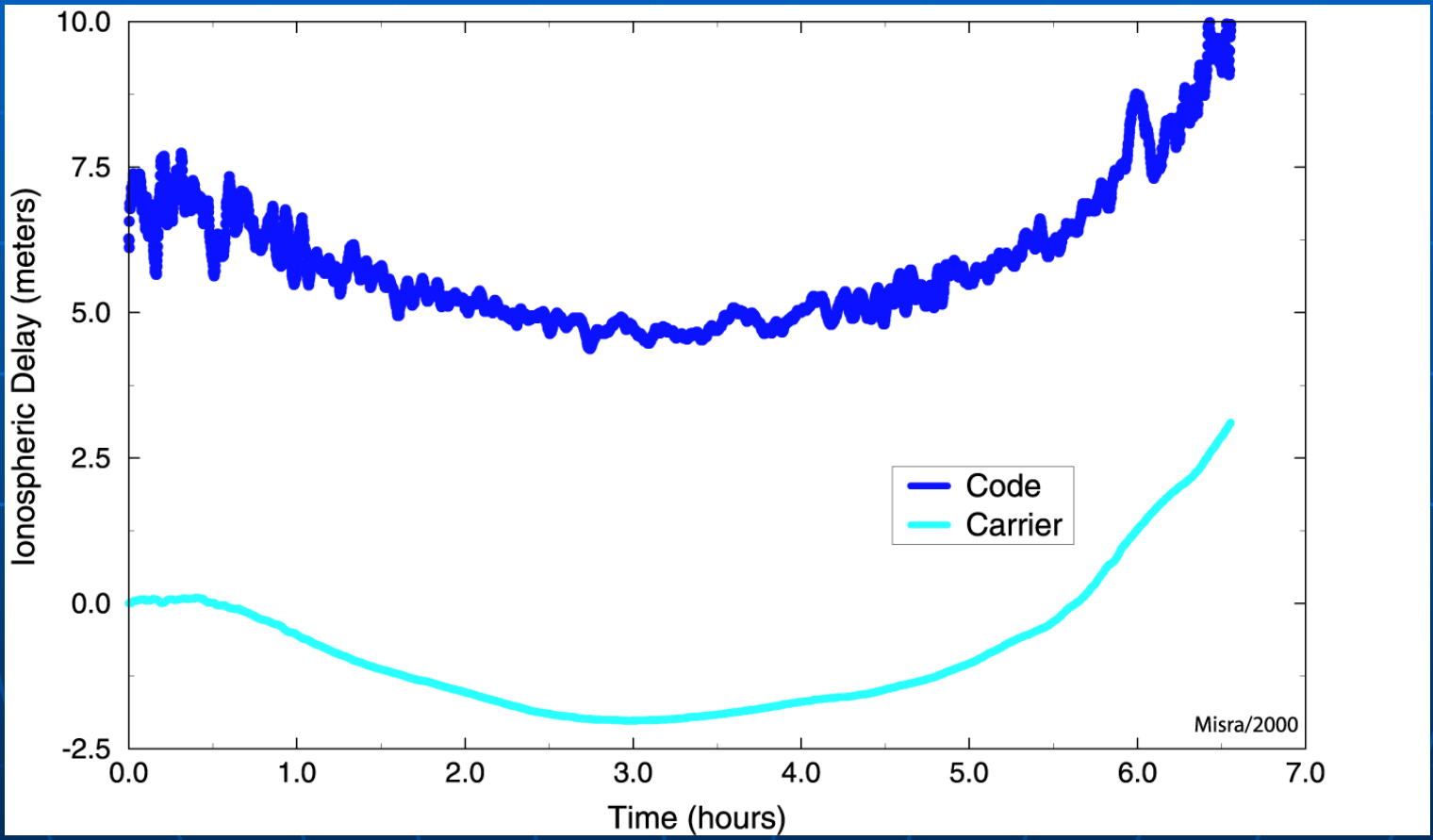
- **Total Electron Content**
- **Scintillation Parameters: S_4 and σ_Φ**

Space-Based Receivers

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

Total Electron Content (TEC) Estimation

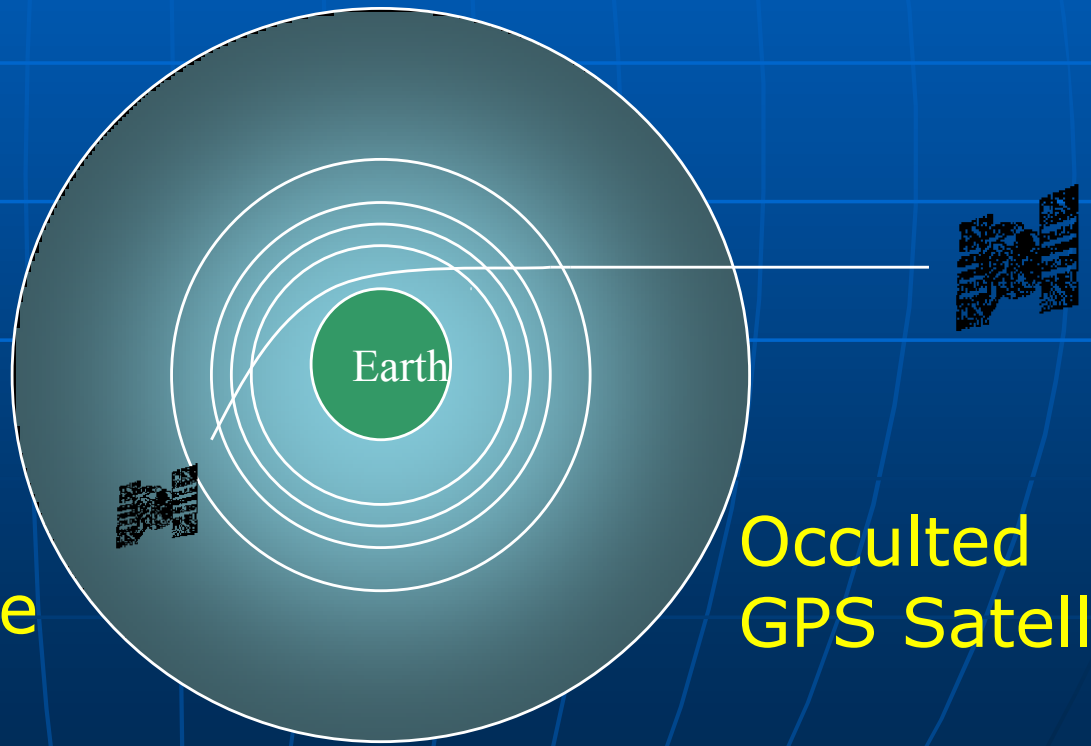
Dual-Frequency Measurements



GPS Occultation

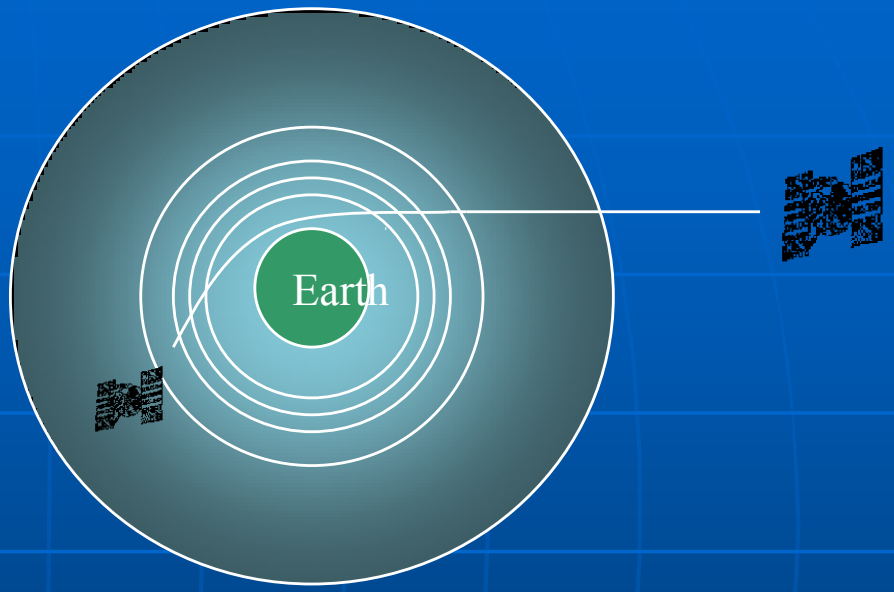
Typical occultation event
last 1-2 min.

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.**

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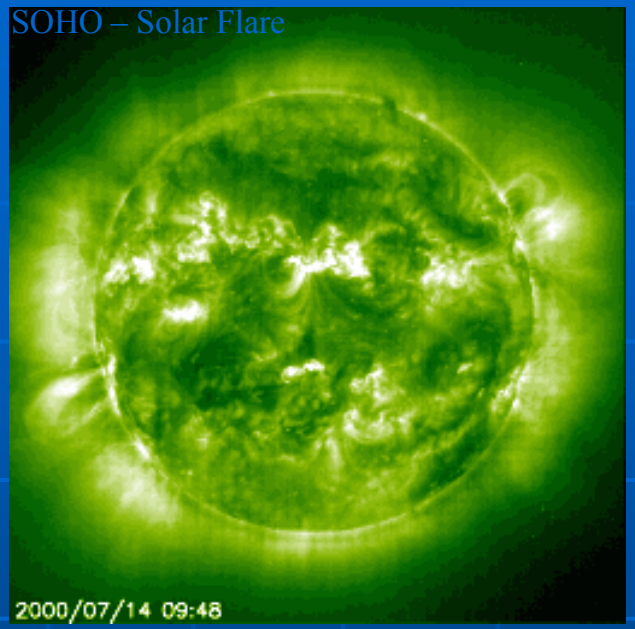
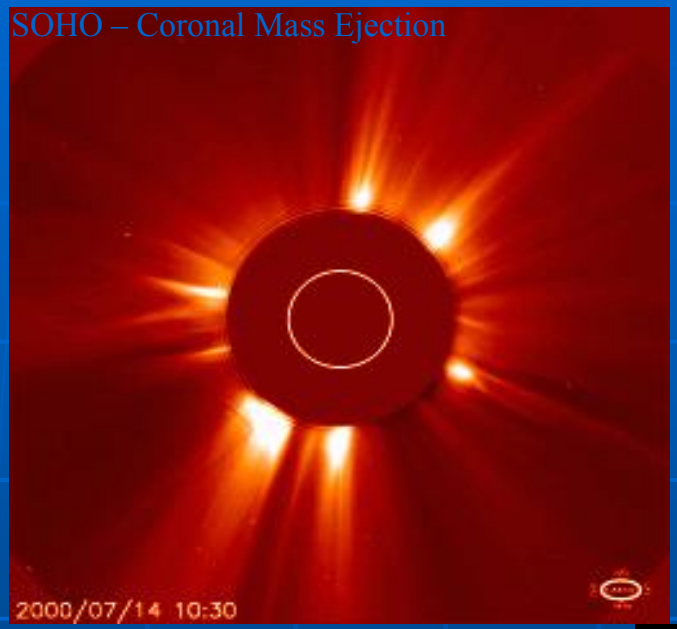
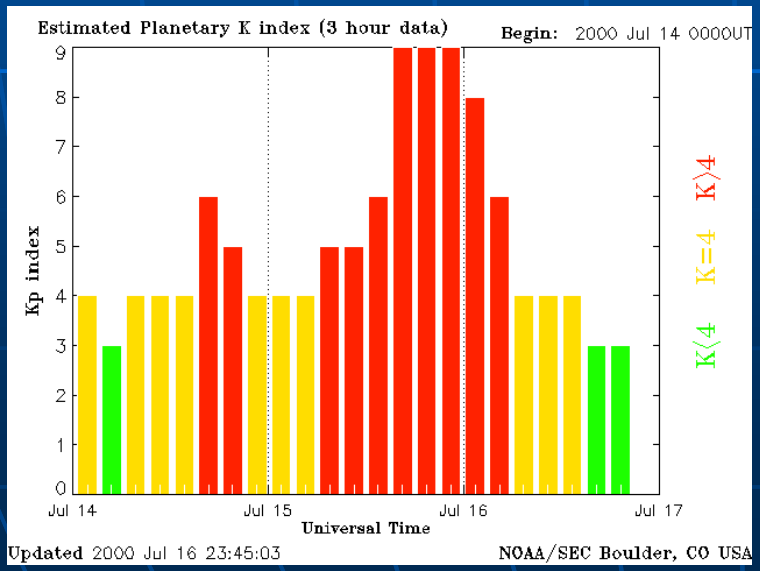
Solar Flare of 14 July 2000

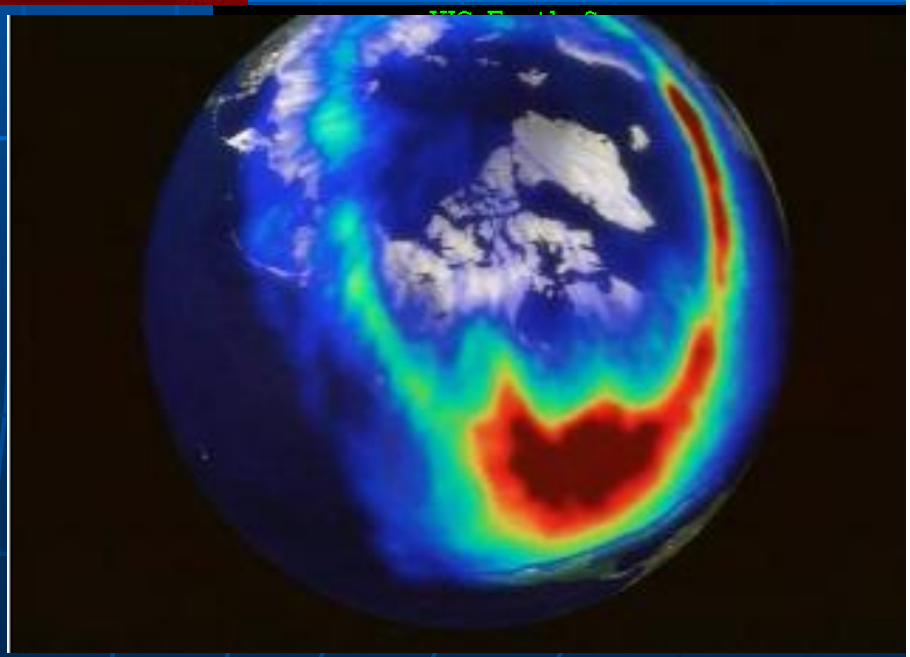




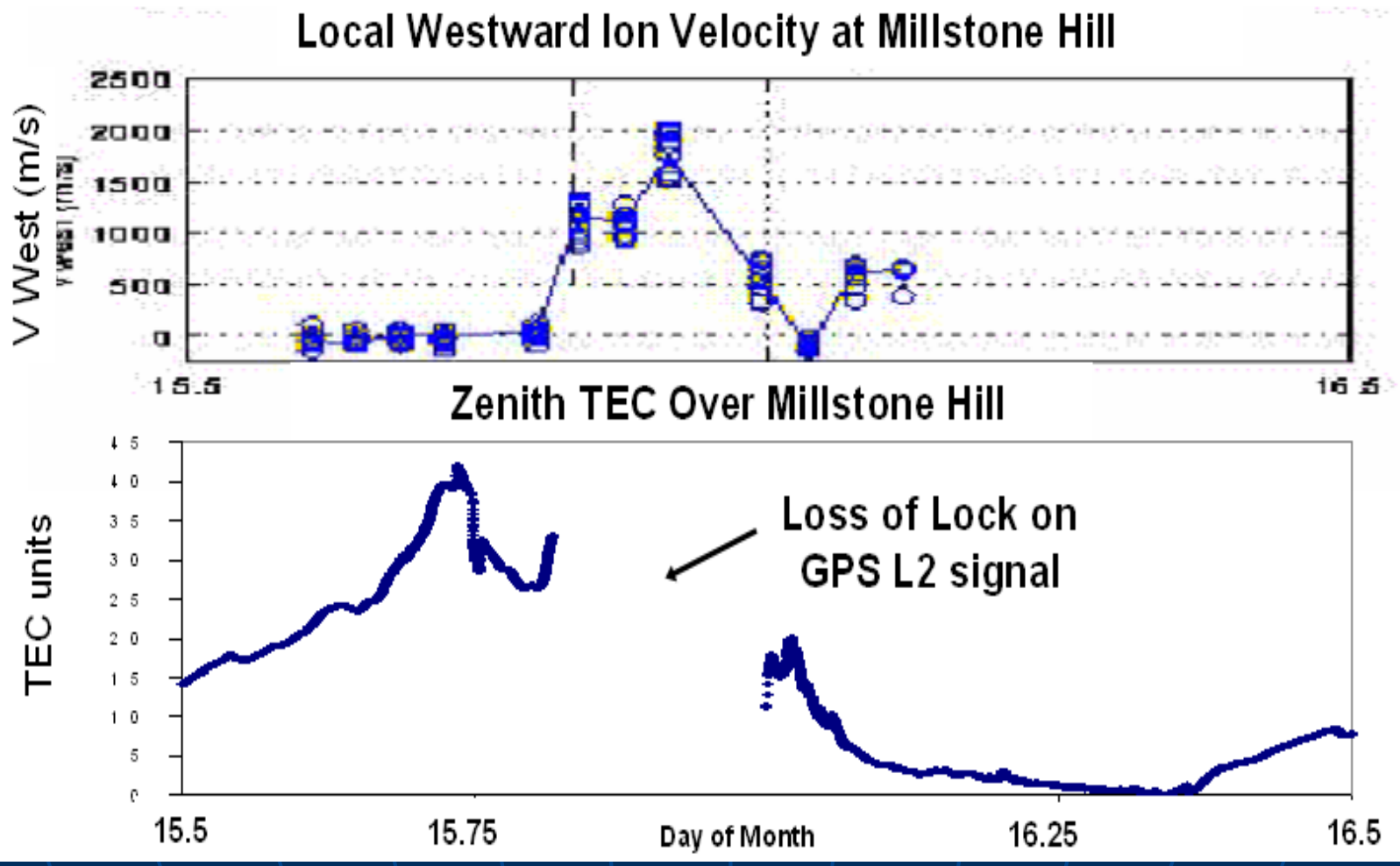
Solar Flare of 14 July 2000
Biggest Solar Storm in Nine Years

Caused very large magnetic storm and ionospheric effects

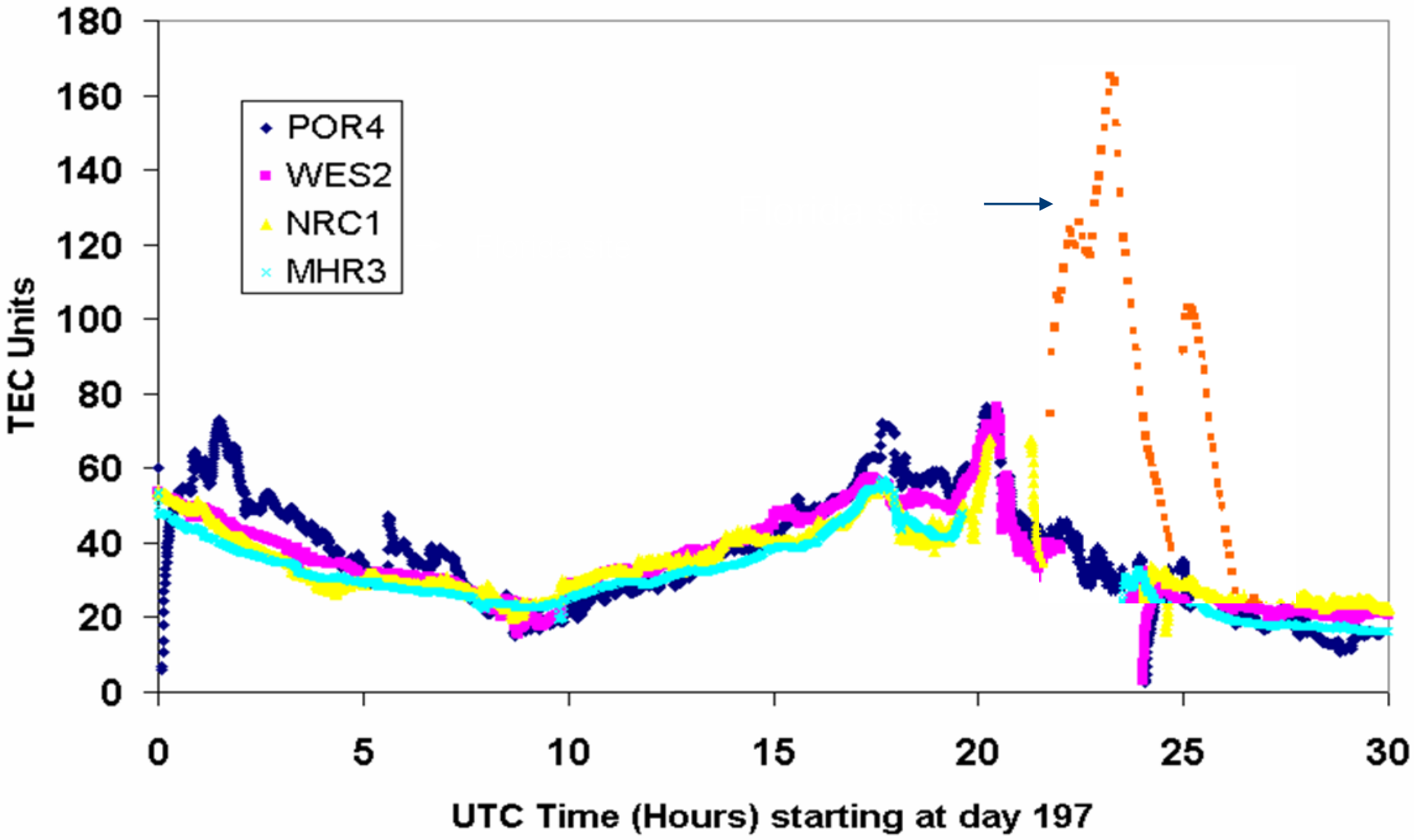




GPS Loss of Lock at Millstone Hill

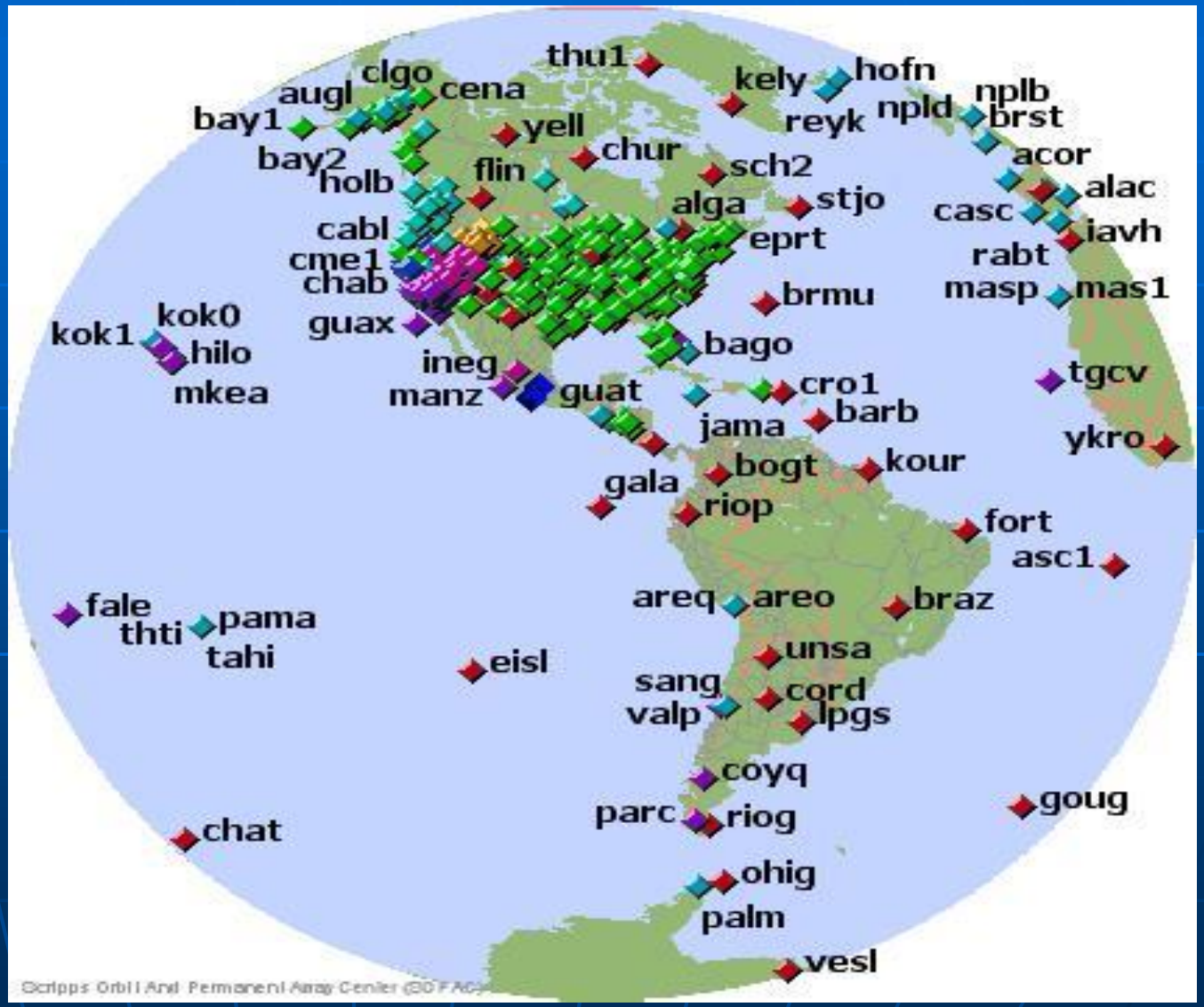


TEC Disturbances on 15 July 2000



Wide Area Distribution of 'Raw' Information

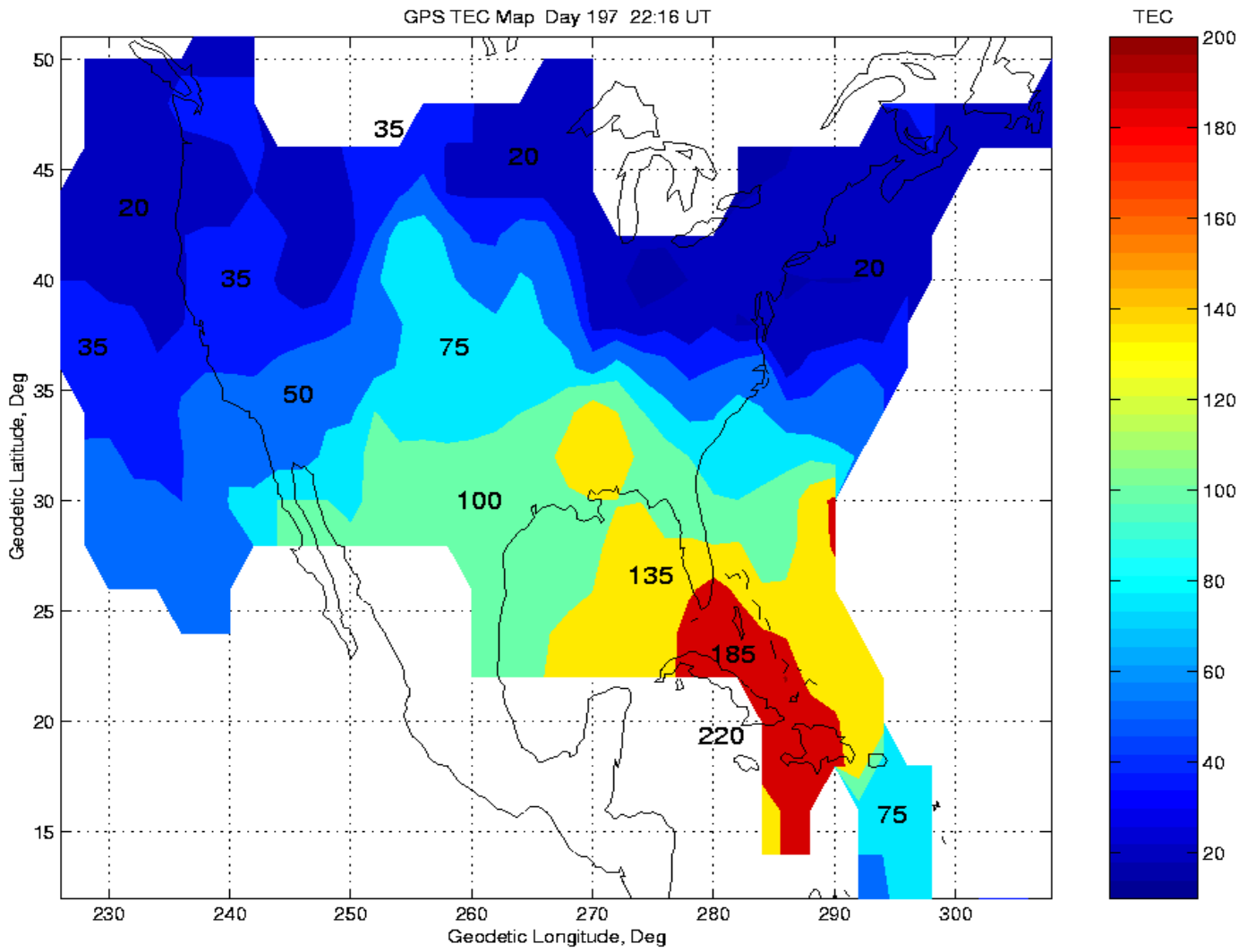
Distributed networks of sensors yield global physics unattainable with single-point measurements



[Coster et al, 2003]

GPS Total Electron Content Map

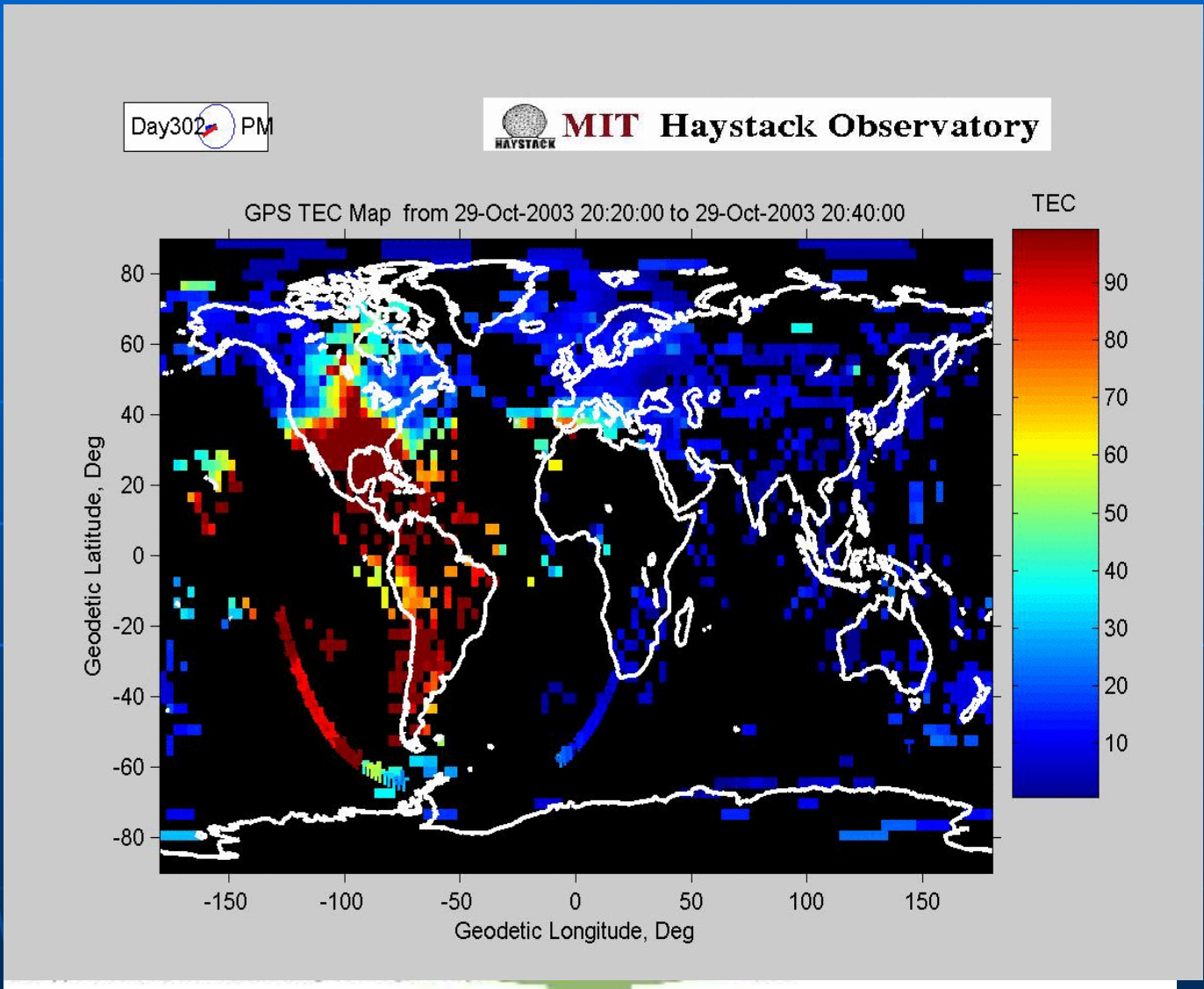
Illustration of Storm Enhanced Density



Wide Area Distribution of 'Raw' Information

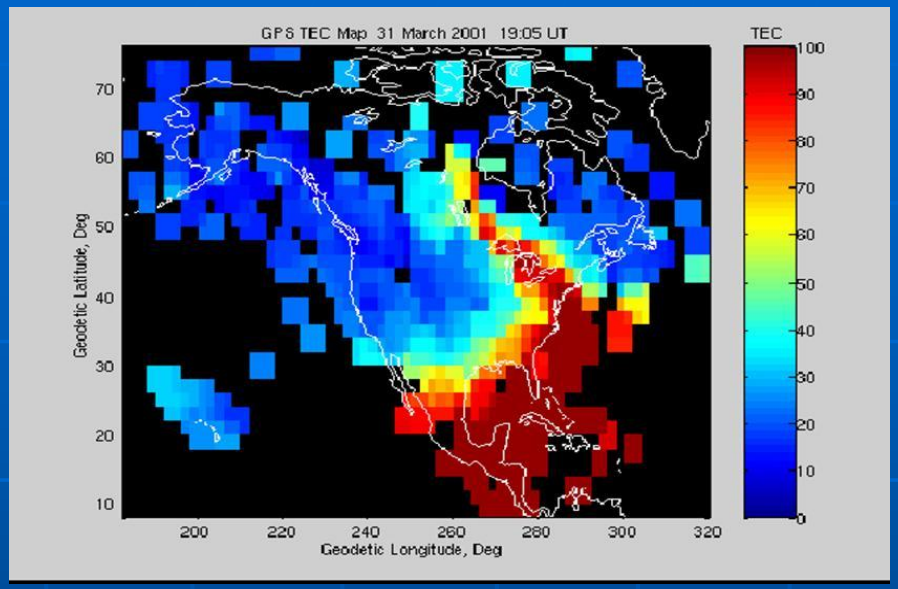
Distributed networks of sensors yield global physics unattainable with single-point measurements

Example :
Global GPS-derived ionospheric mapping during geomagnetic disturbances

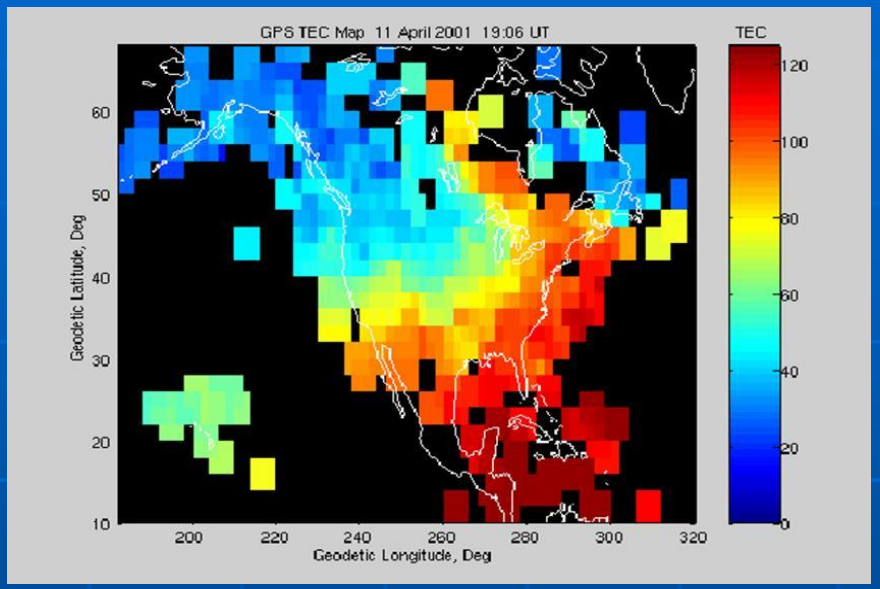


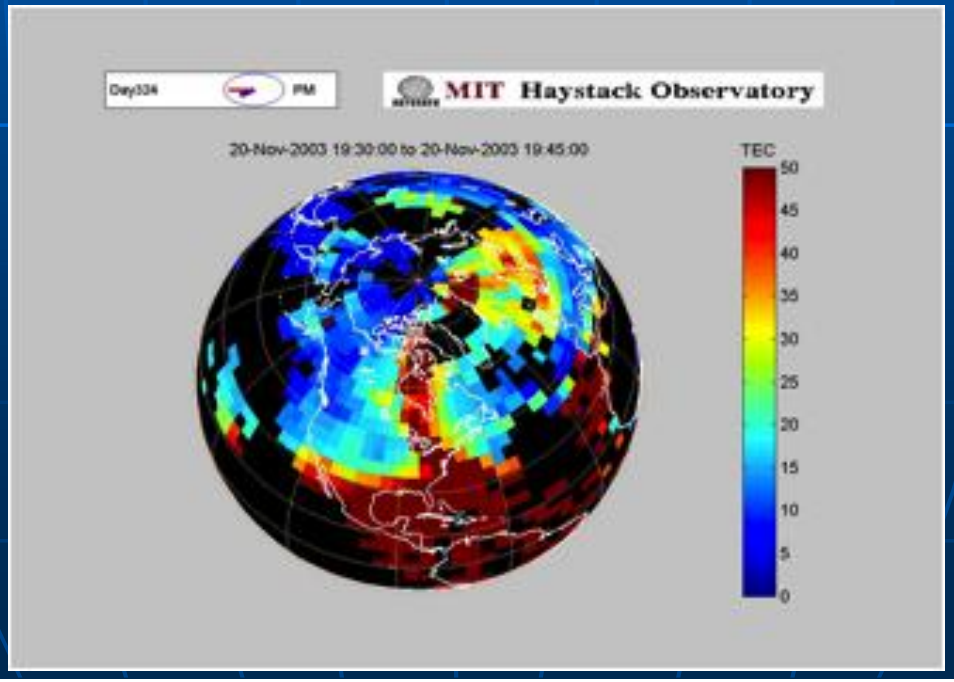
[Coster et al, 2003]

Day 90, 2001



Day 101, 2001





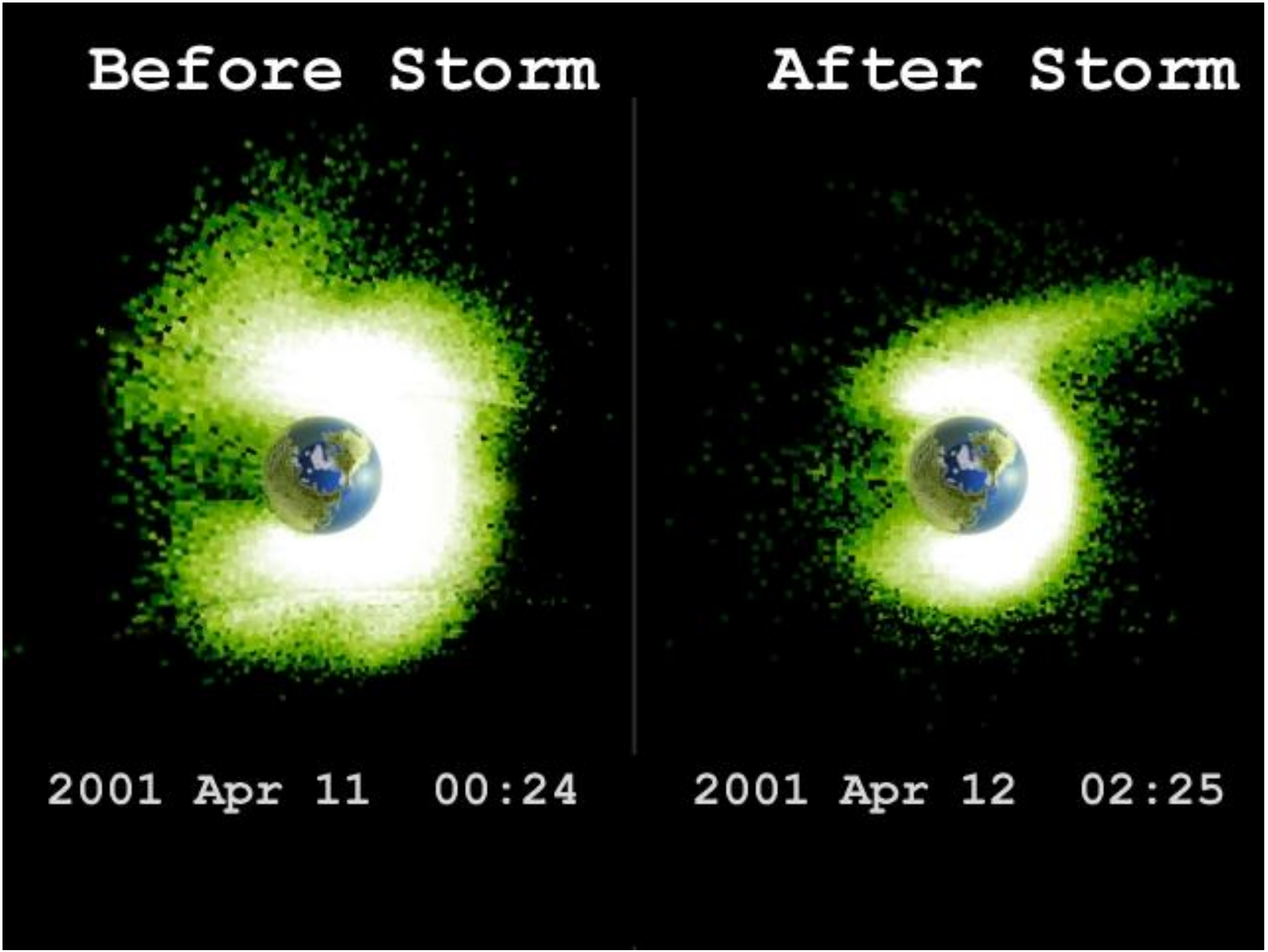
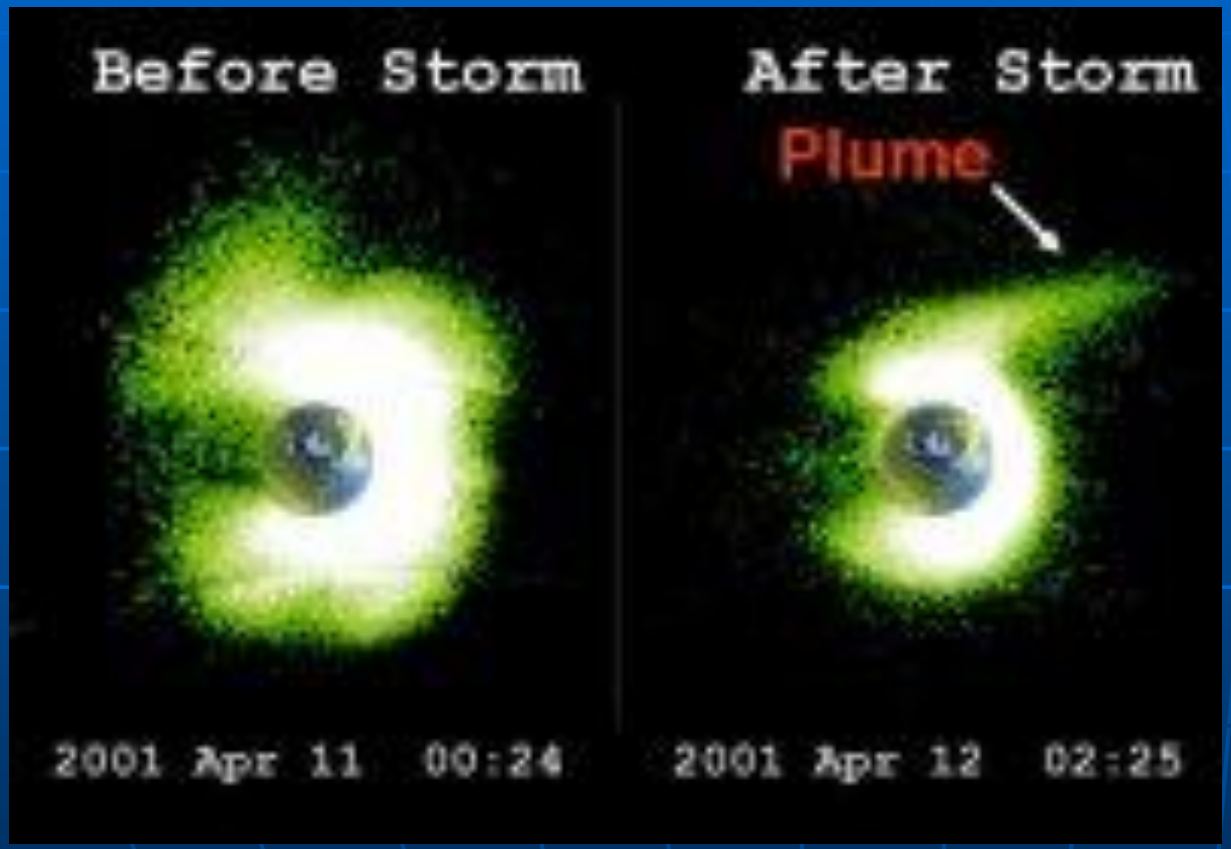
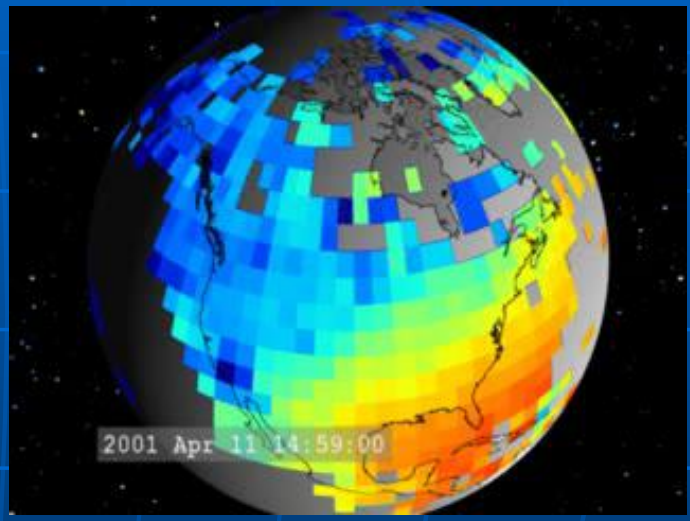
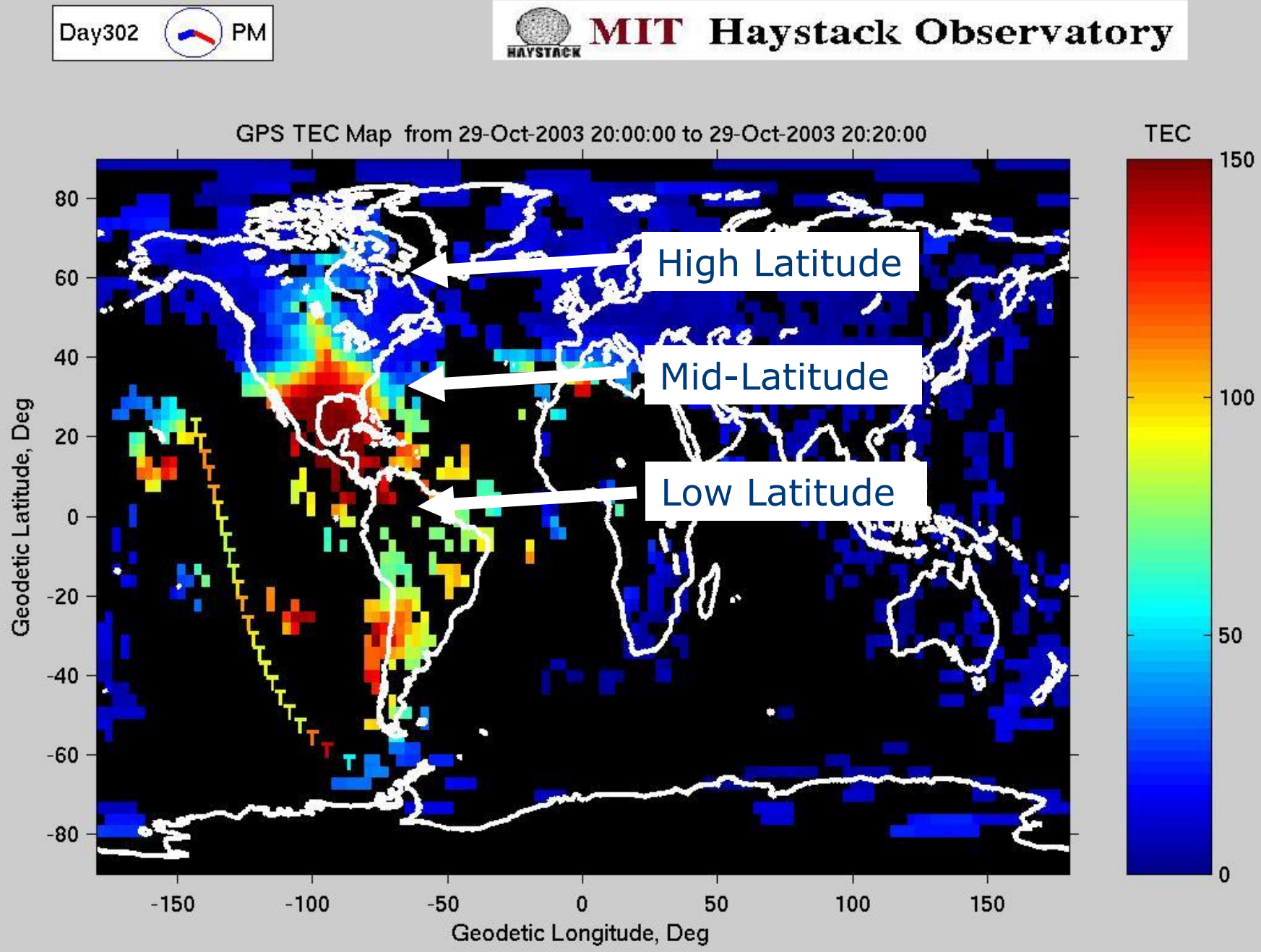

Before Storm
After Storm
2001 Apr 11 00:24
2001 Apr 12 02:25

IMAGE Data of Plasmasphere






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
High Latitude
Mid-Latitude
Low Latitude
Geodetic Latitude, Deg
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150
Geodetic Longitude, Deg

Aurora in New Brunswick, Canada

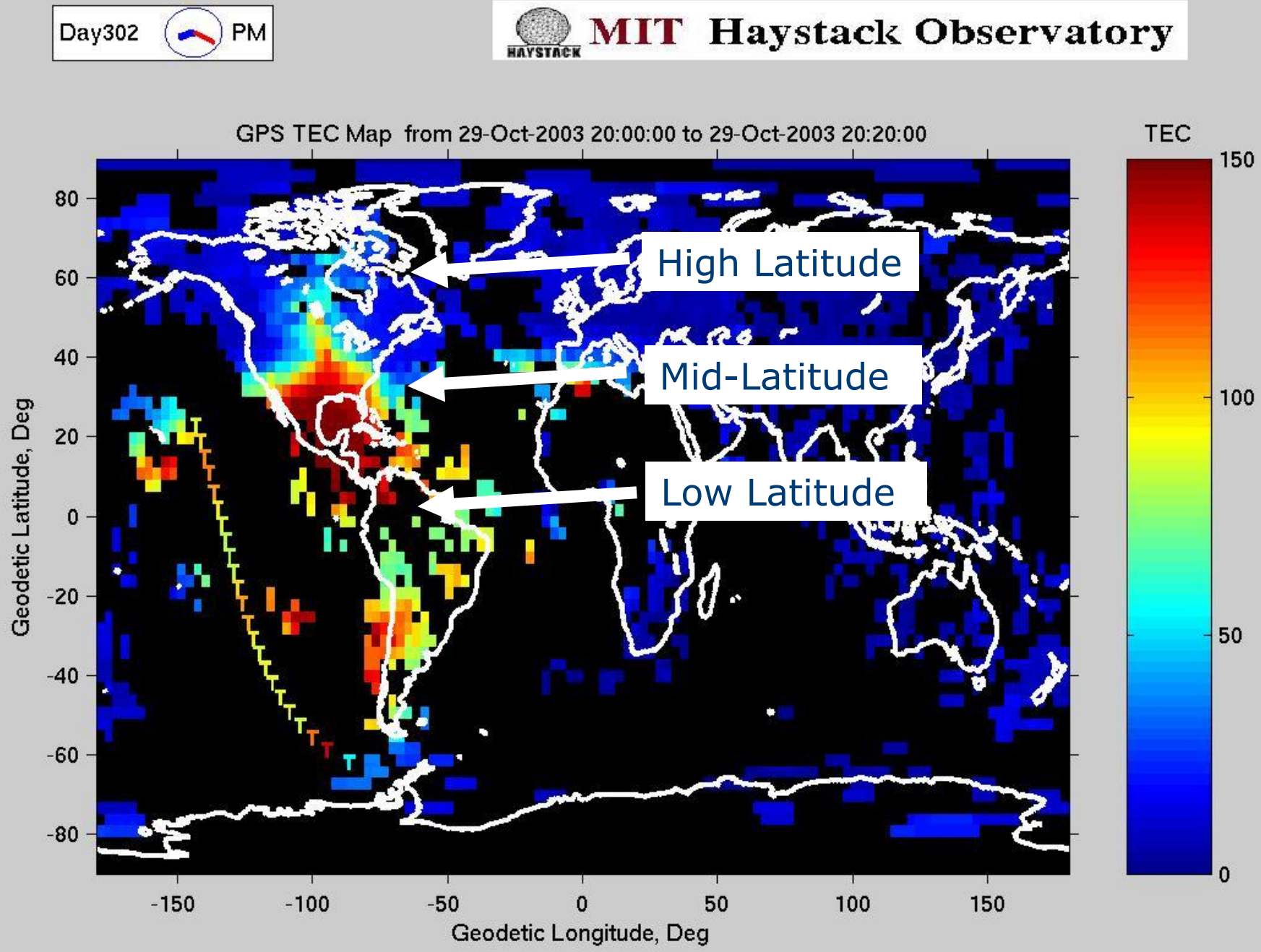
30 October 2003

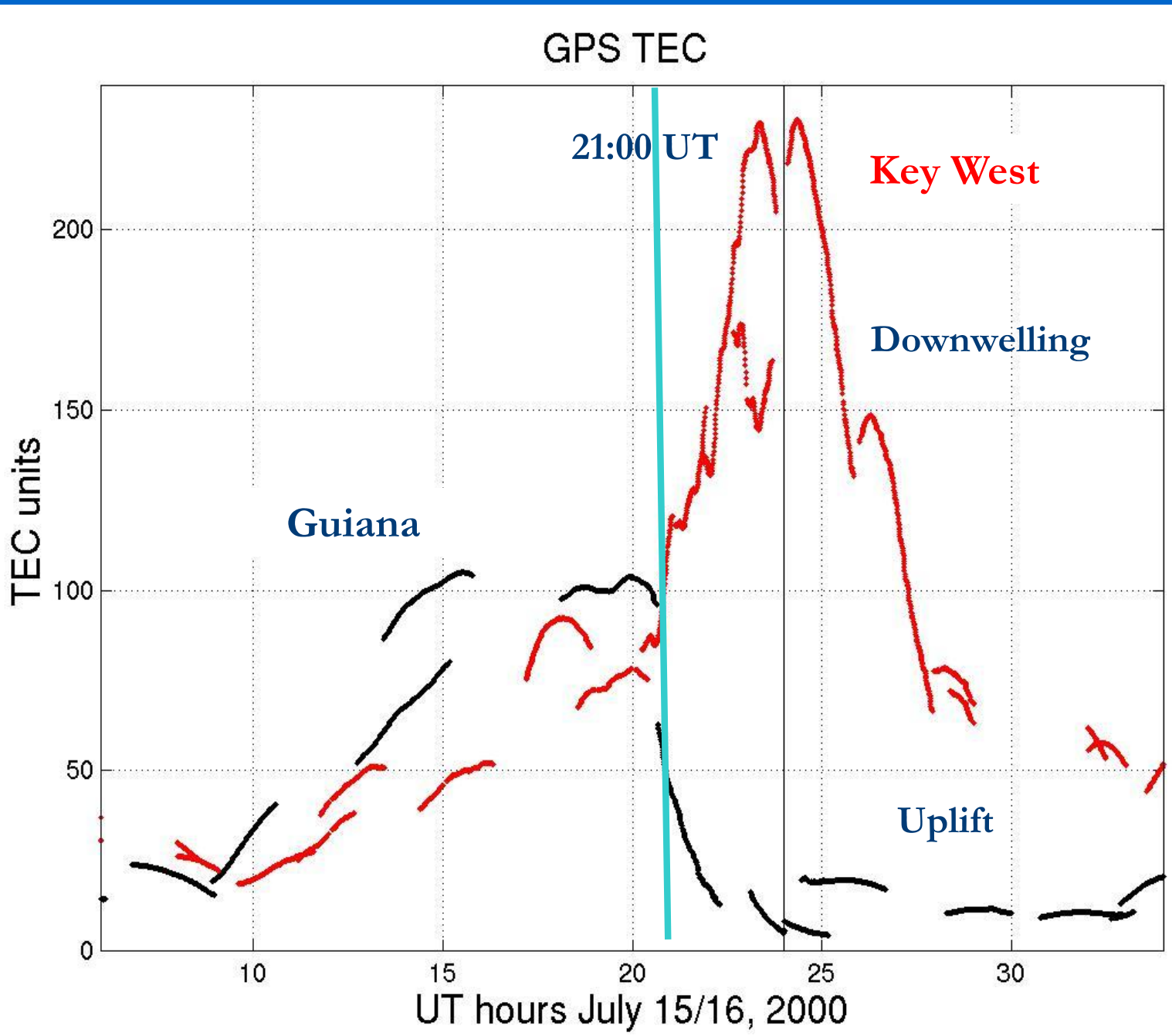
Socorro New Mexico 20 Nov 2003

(from astronomy picture of the day)

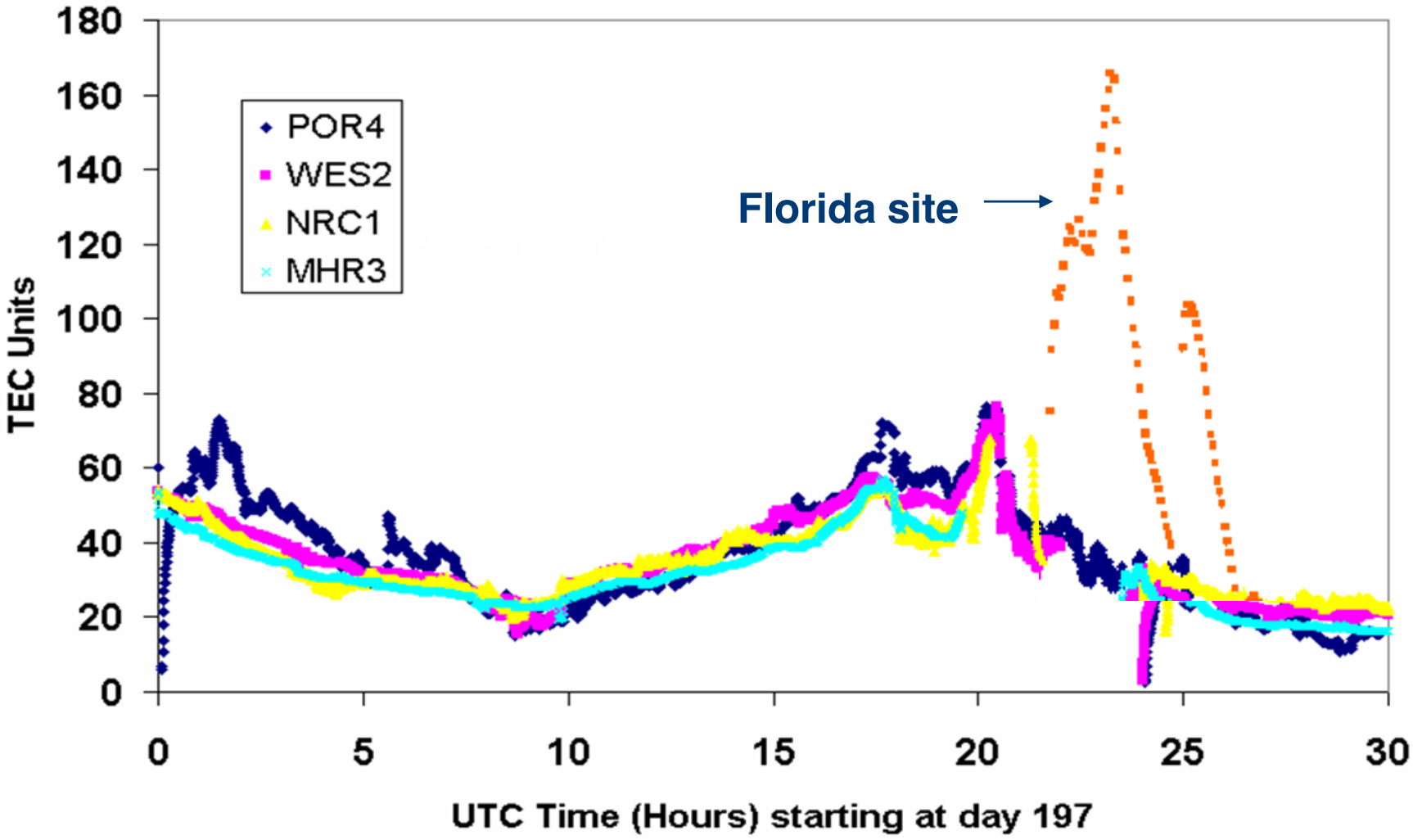
West Texas 15 Sept 2000 near El Paso Texas

(from astronomy picture of the day)

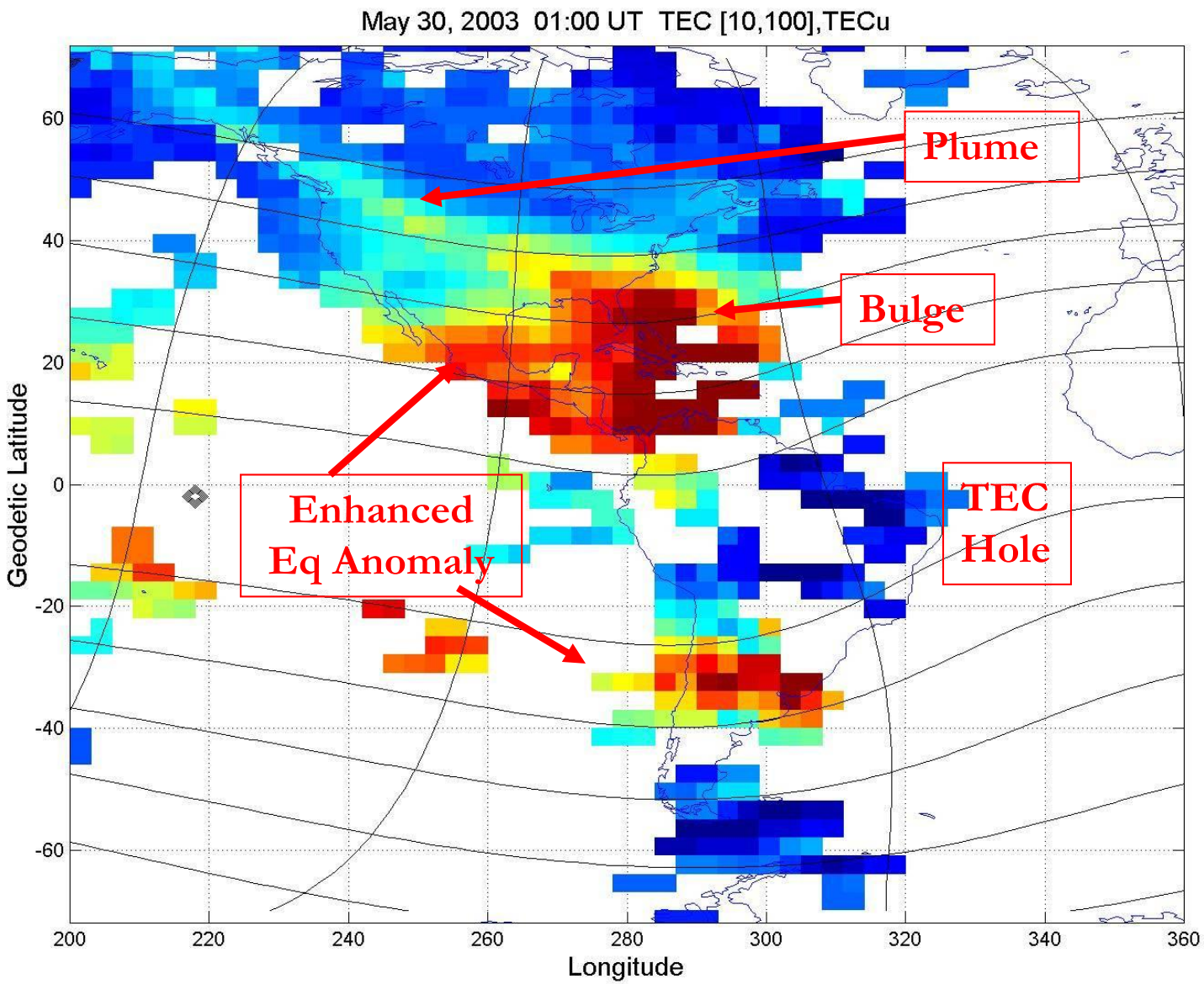

Day302
PM
MIT Haystack Observatory
GPS TEC Map from 29-Oct-2003 20:00:00 to 29-Oct-2003 20:20:00
TEC
150
100
50
0
High Latitude
Mid-Latitude
Low Latitude
Geodetic Latitude, Deg
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150
Geodetic Longitude, Deg


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

TEC Disturbances on 15 July 2000



Inner Magnetosphere – Low Latitude View



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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**

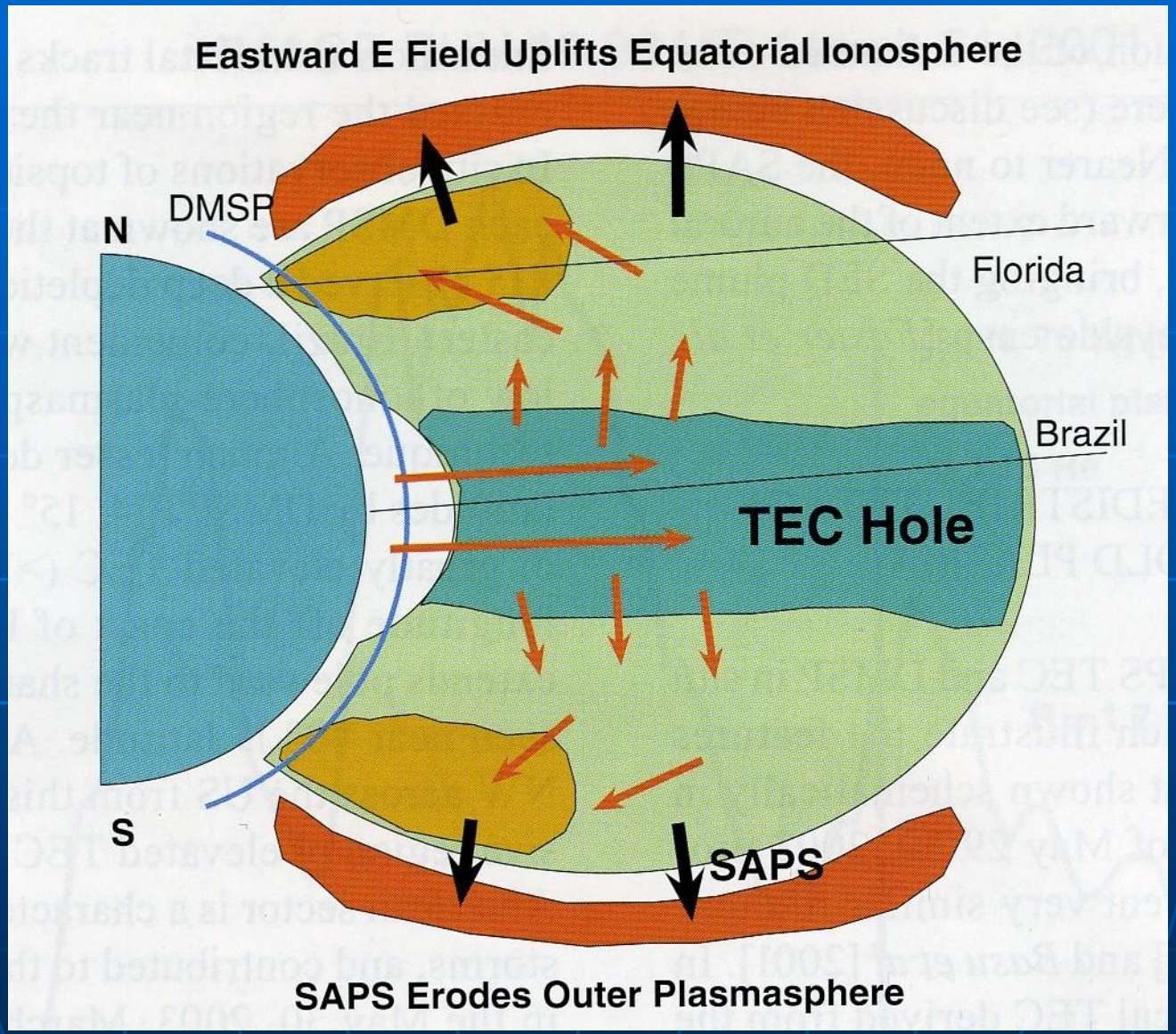
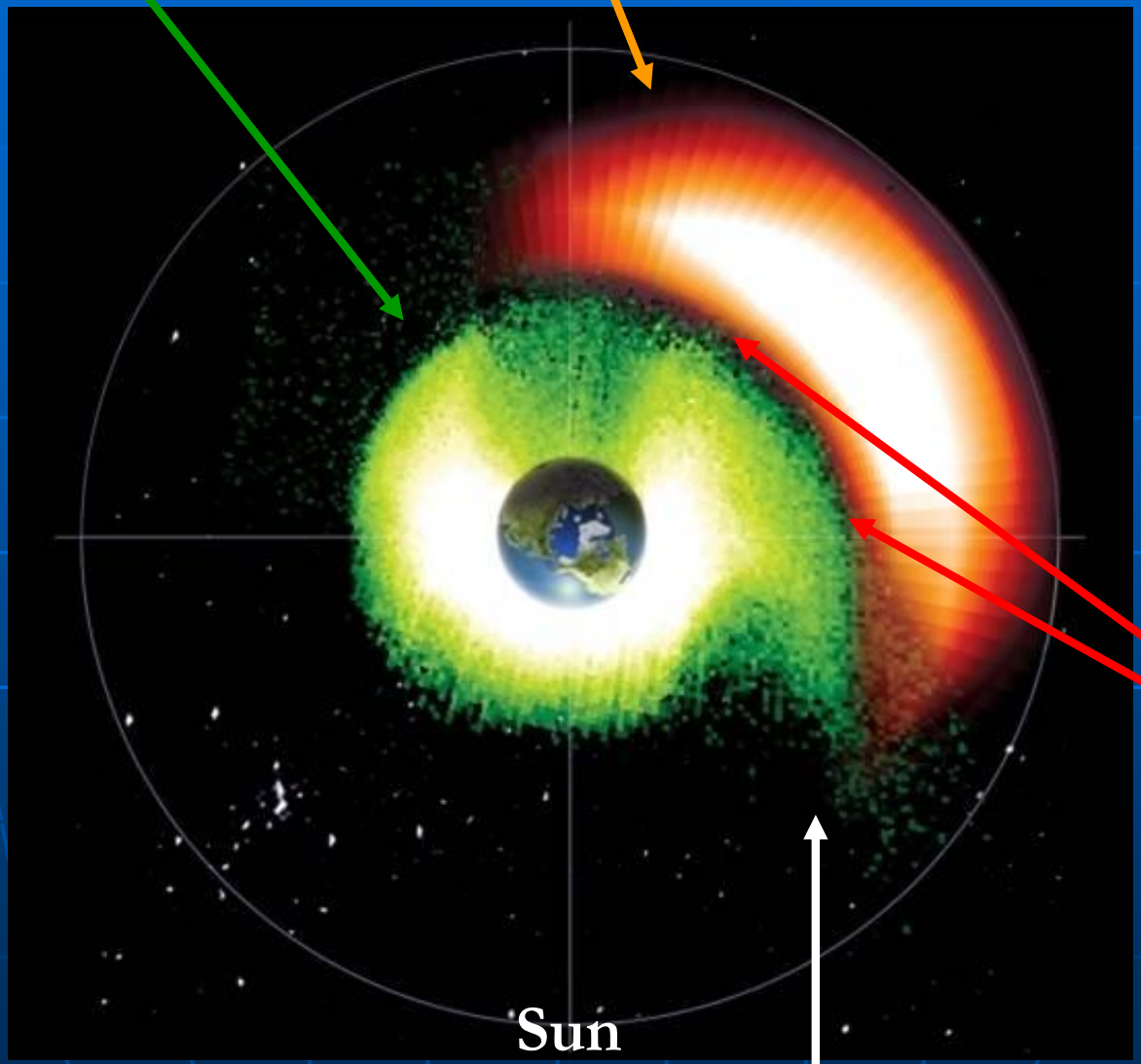


Figure courtesy of J. Foster

Plasmasphere / Ring Current Interactions

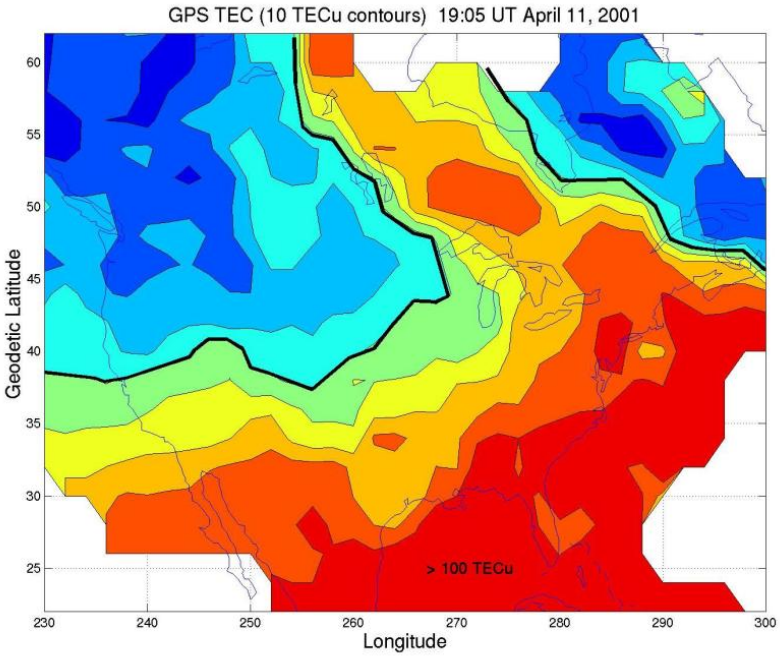


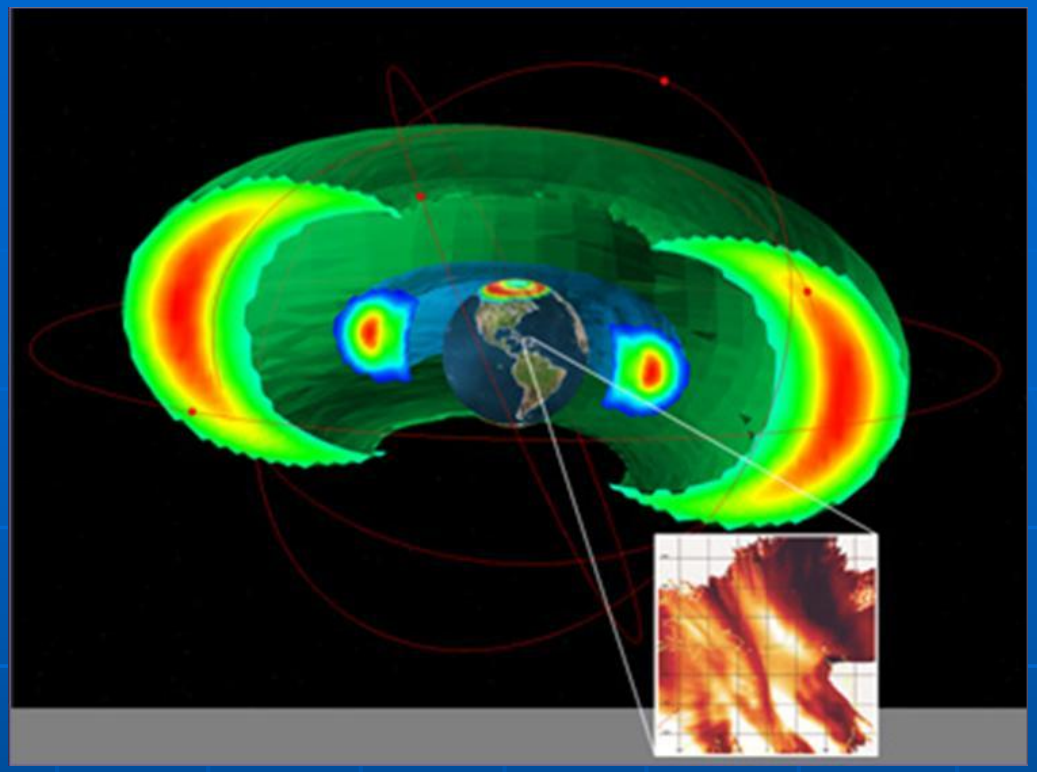
April 17, 2002
NASA IMAGE

SAPS Channel

Plasmasphere Erosion Plume

(Merged image courtesy J. Goldstein)





Magnetosphere Ionosphere Atmosphere Coupling

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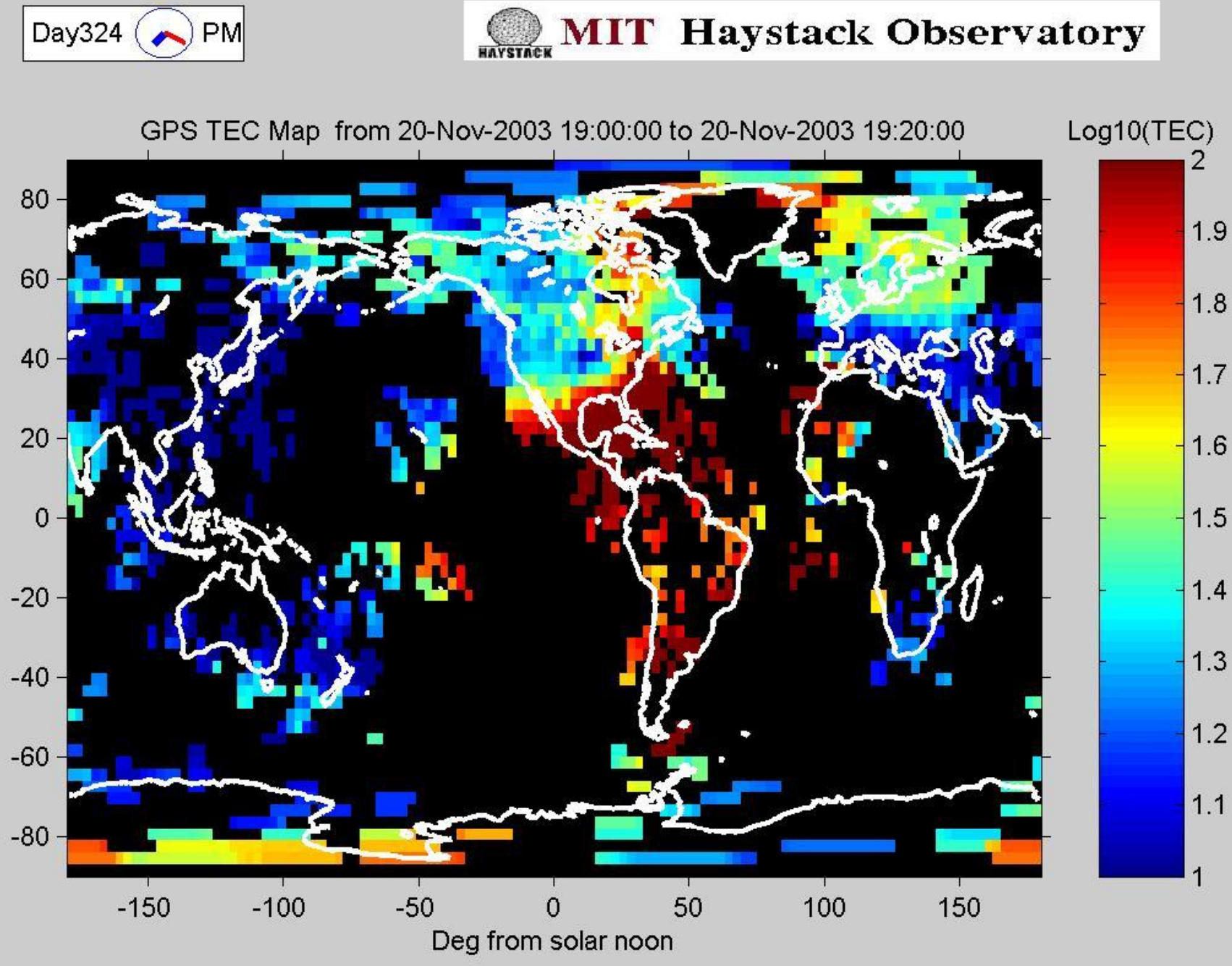
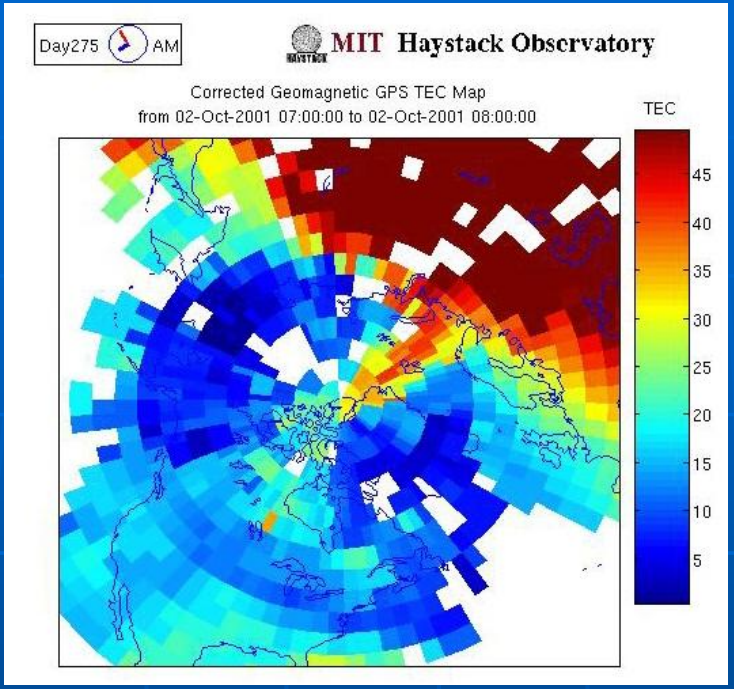
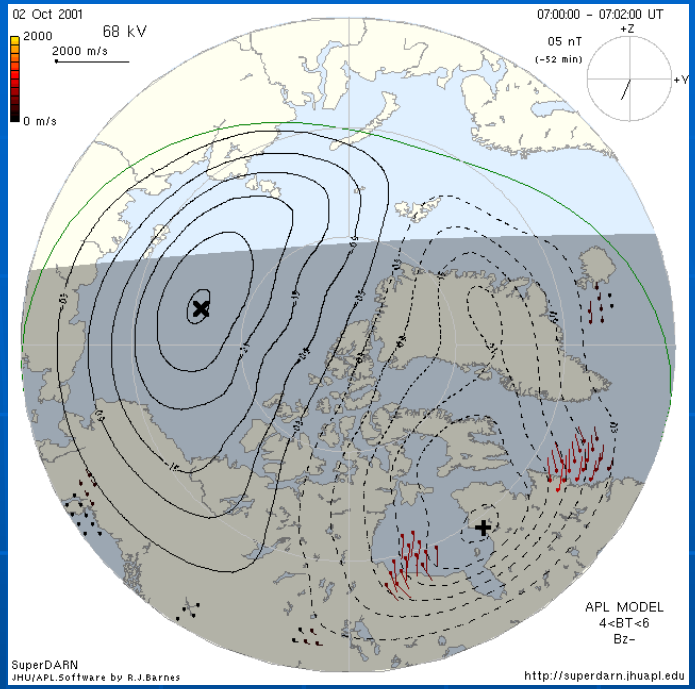

Day324
PM
MIT Haystack Observatory
GPS TEC Map from 20-Nov-2003 19:00:00 to 20-Nov-2003 19:20:00
Log10(TEC)
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150
Deg from solar noon

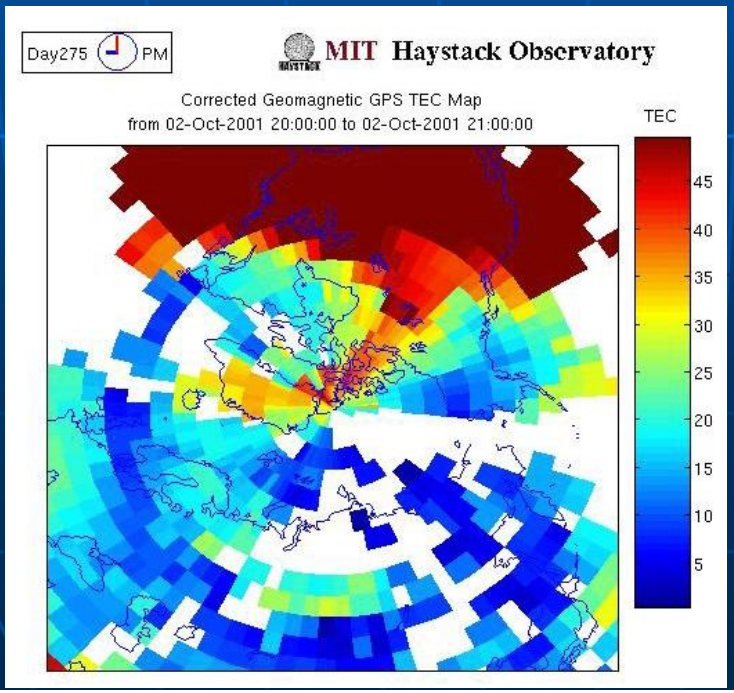
Northern Europe and American Sector SED Plumes

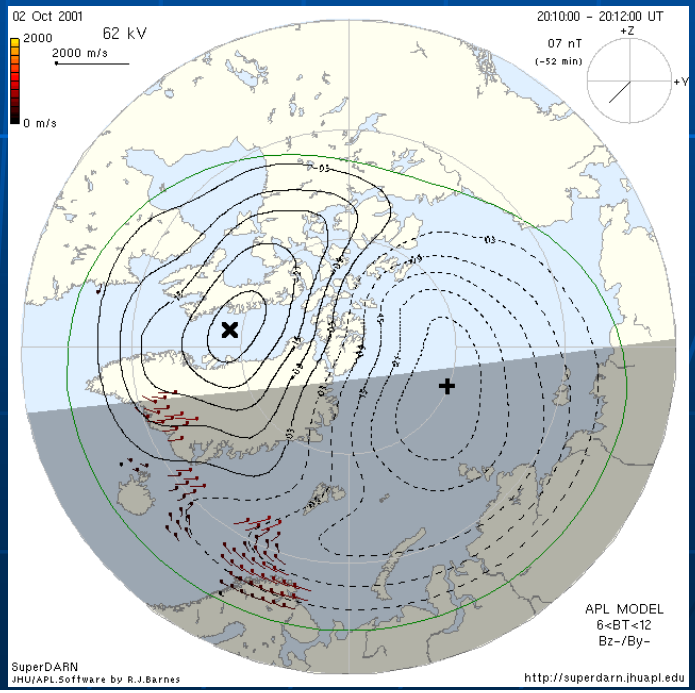
Northern Europe



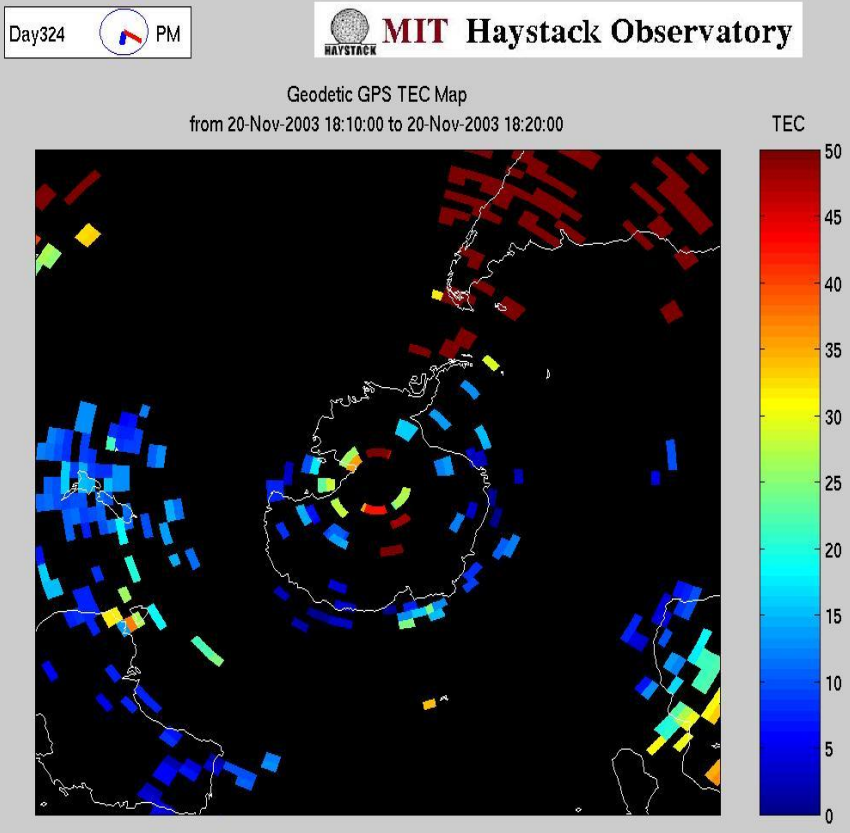


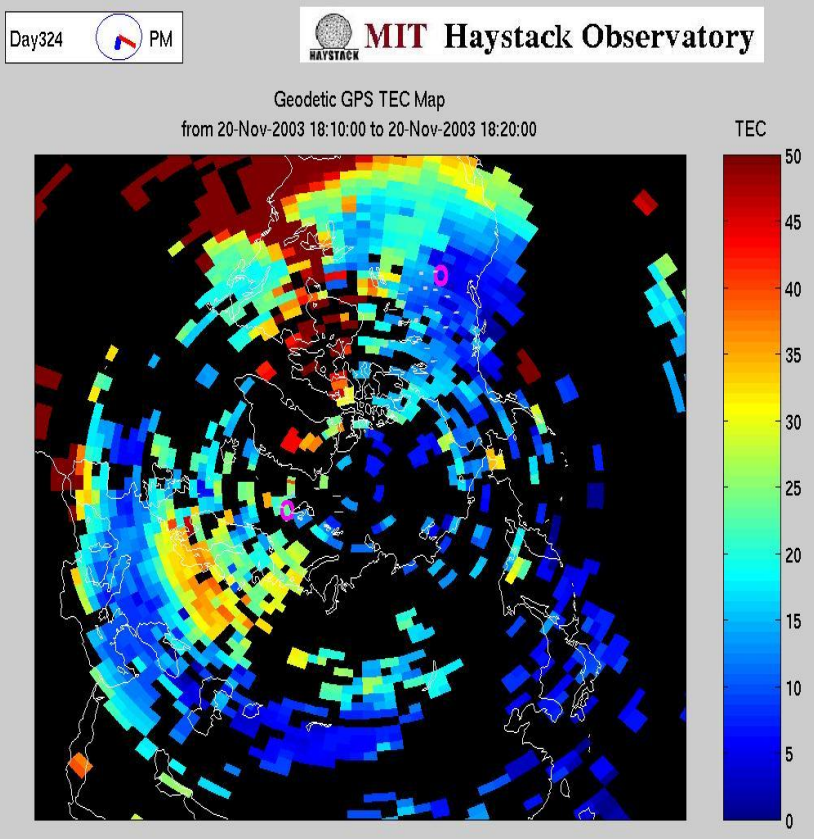
American Sector





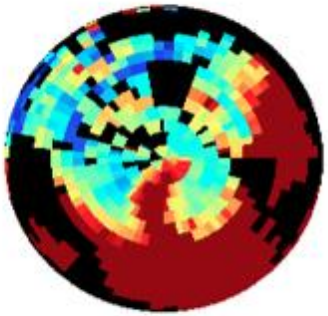
20 Nov 2003 18:20 UT





26 Sep 2011

North Pole



19:00-19:30 UT
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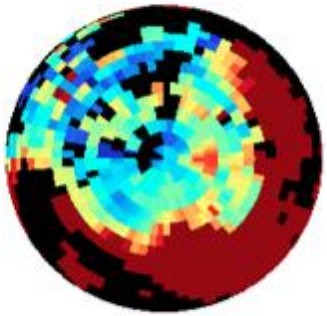

20:00-20:30 UT
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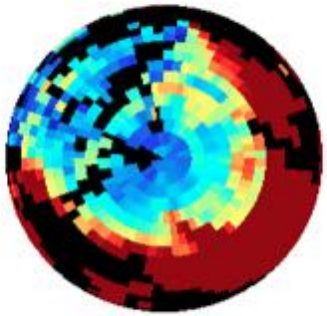

21:00-21:30 UT
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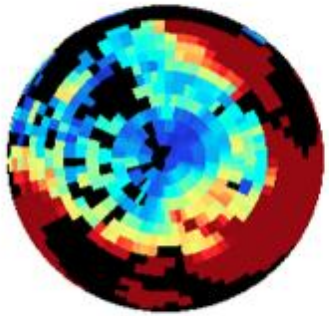

22:00-22:30 UT
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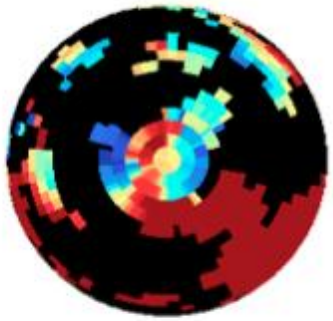
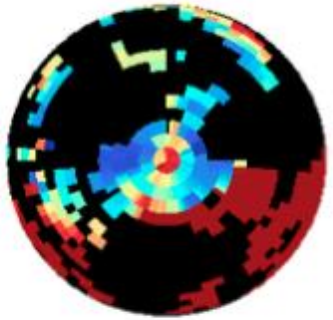
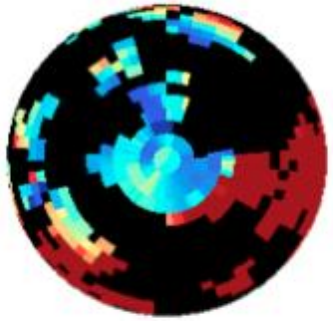
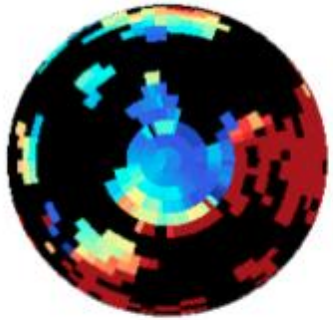


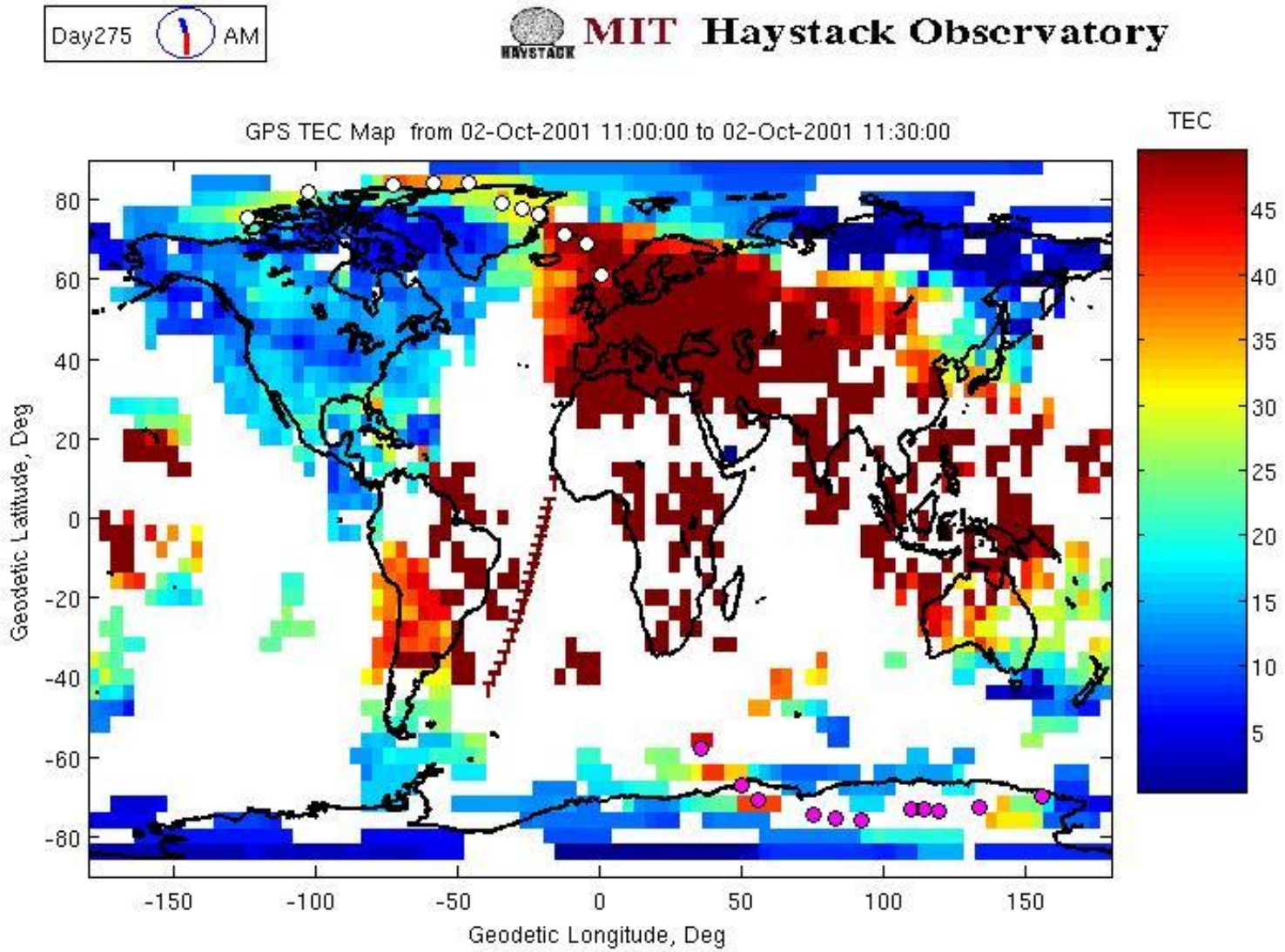




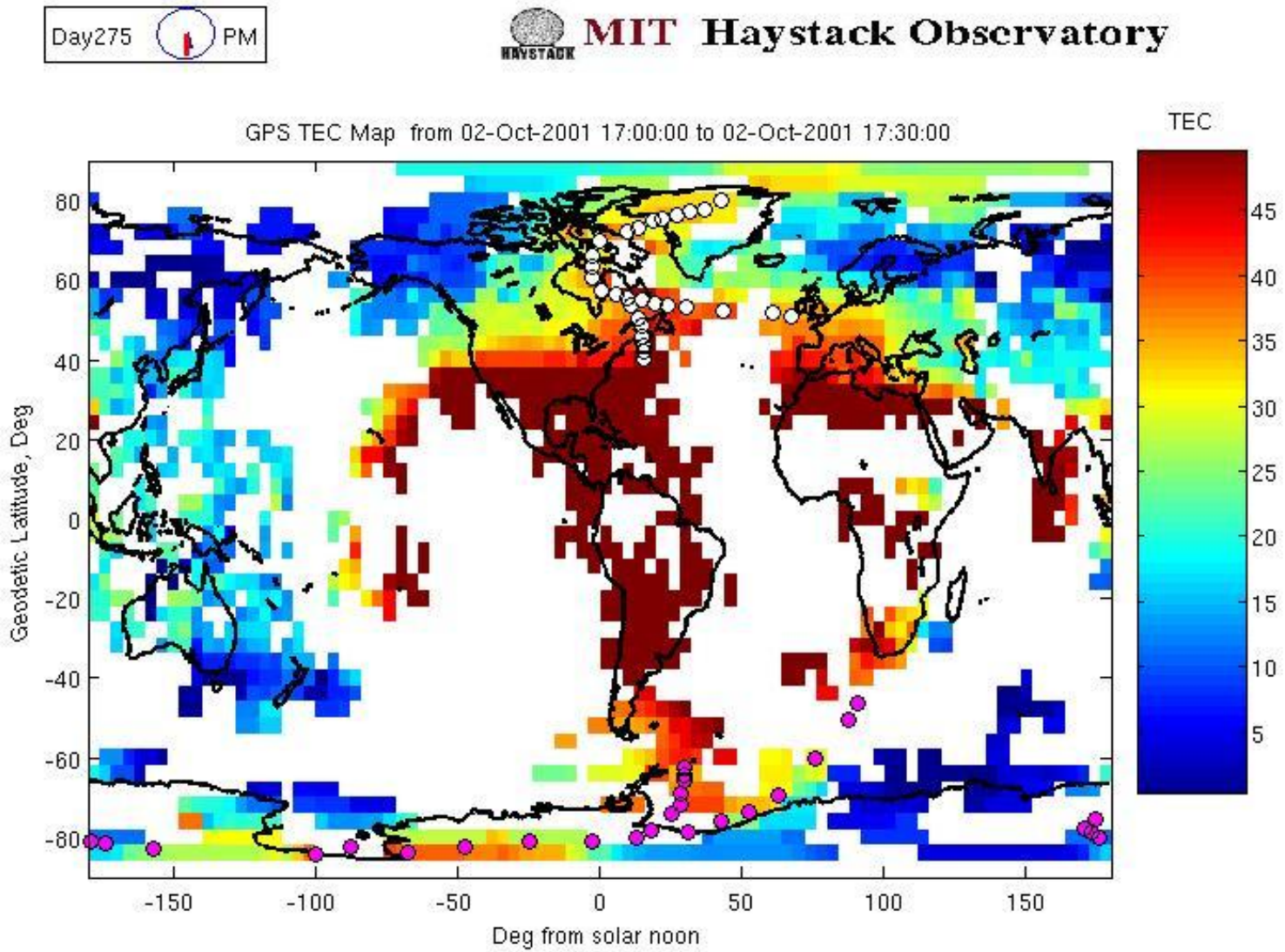


South Pole

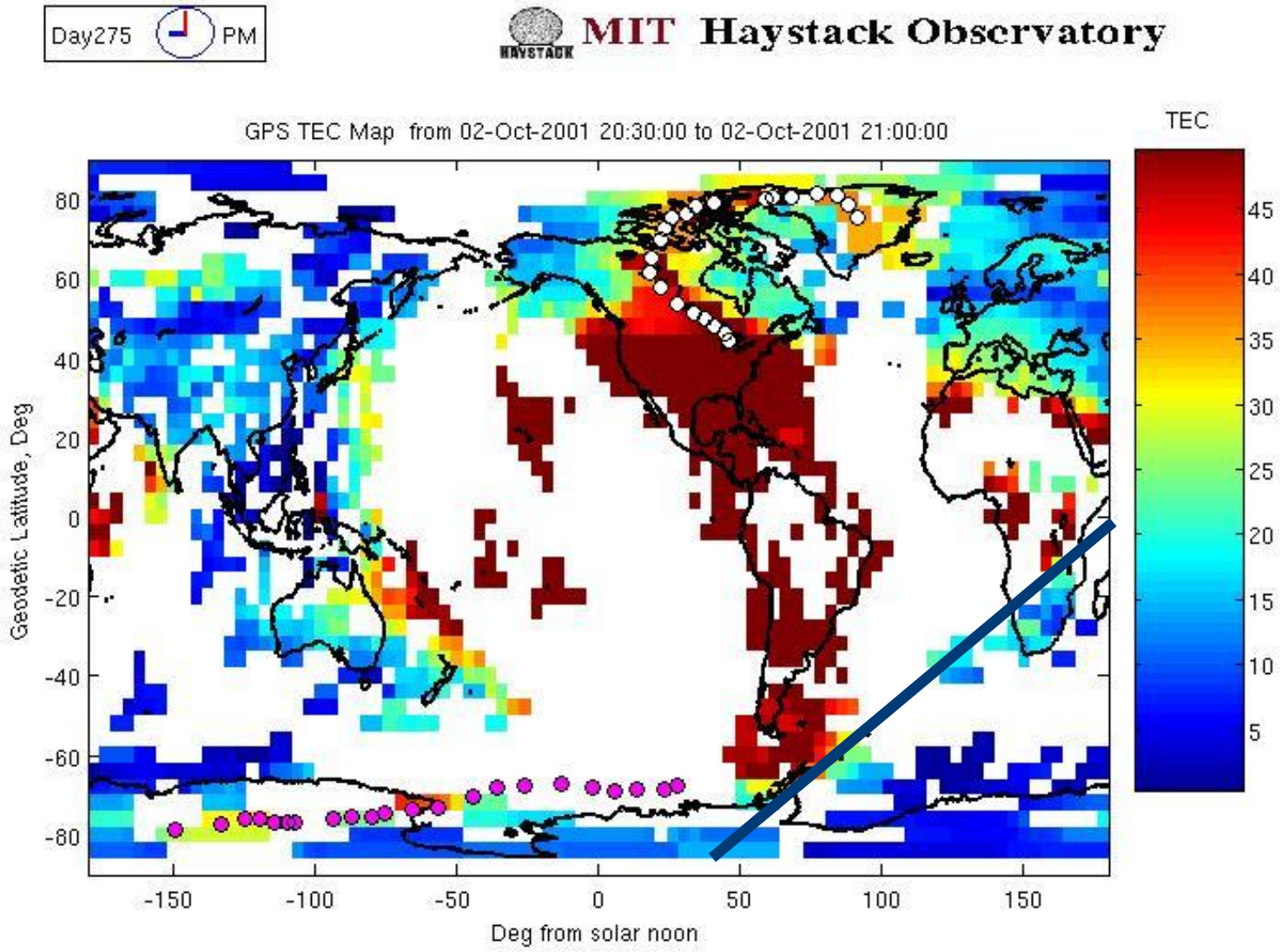
Conjugacy Examples

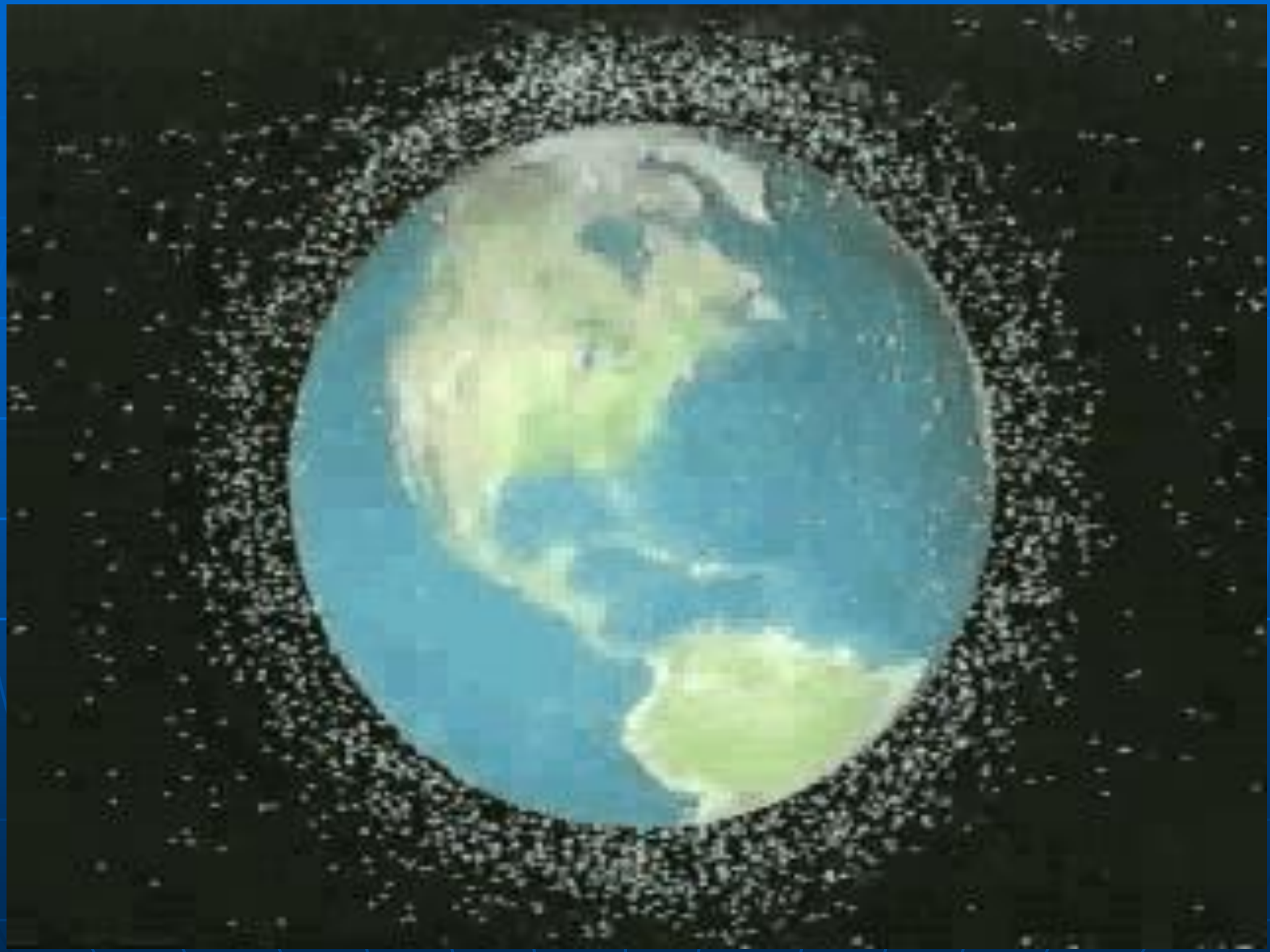


Conjugacy Examples



Conjugacy Examples





From the Sun to the Earth