The Ionosphere and its Impact on Communications and Navigation

Tim Fuller-Rowell
NOAA Space Environment Center and
CIRES, University of Colorado

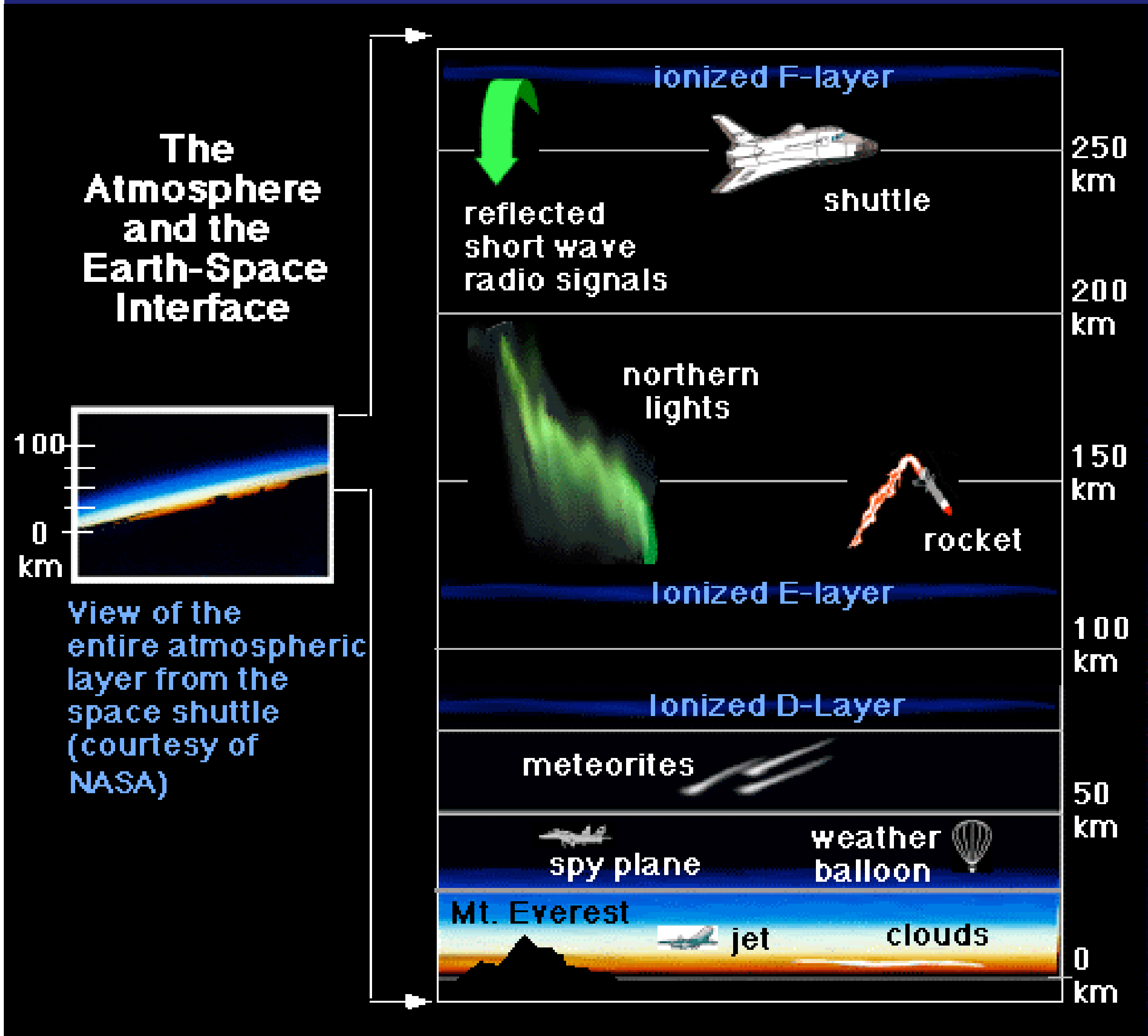
Customers for Ionospheric Information

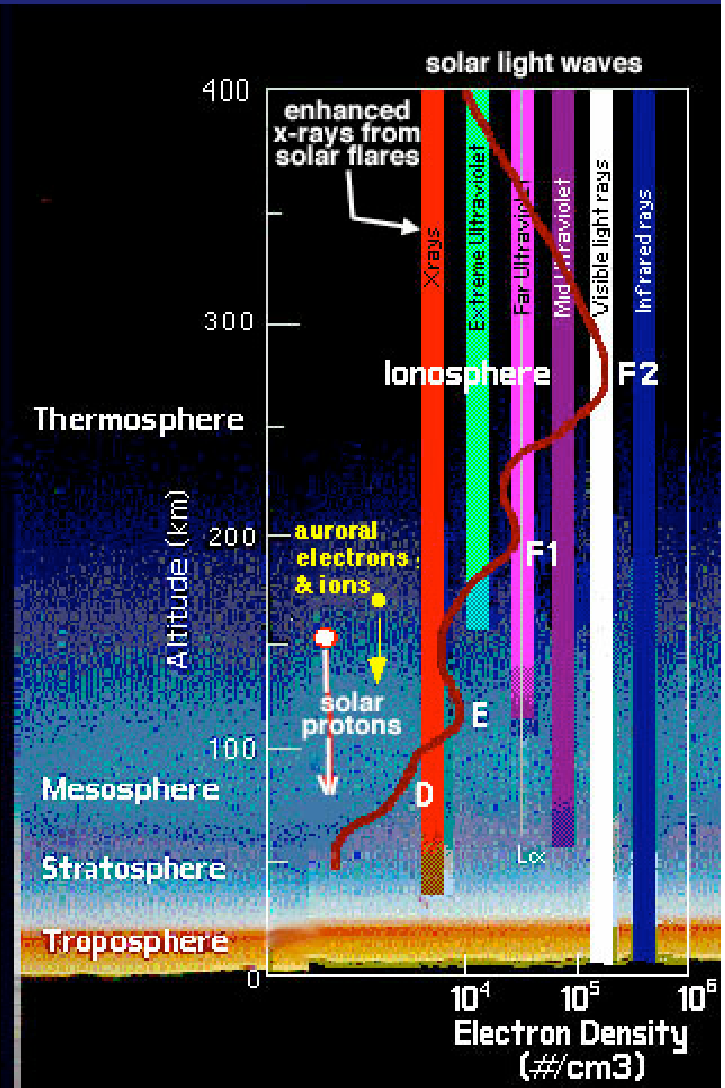
- **High Frequency (HF) Communication (3-30MHz)**
  - ground-to-ground or air-to-ground communication
  - establish accurate maximum useable frequencies
  - support automatic link establishment systems
    - e.g., civilian aviation, maritime, frequency managers
- **Single Frequency GPS Positioning and Navigation**
  - single frequency potential sub-meter accuracy positioning
    - e.g., civil aviation, advanced vehicle tracking, potential for E911 improvements
- **Dual Frequency GPS Positioning and Navigation**
  - decimeter accuracy 10-50 cm
    - e.g., real-time kinematic (RTK), autonomous transportation, off-shore drilling and exploration
  - rapid centimeter accuracy positioning 1-2 cm
    - e.g., surveyors, possible InSAR (land radar) applications

Customers for Ionospheric Information

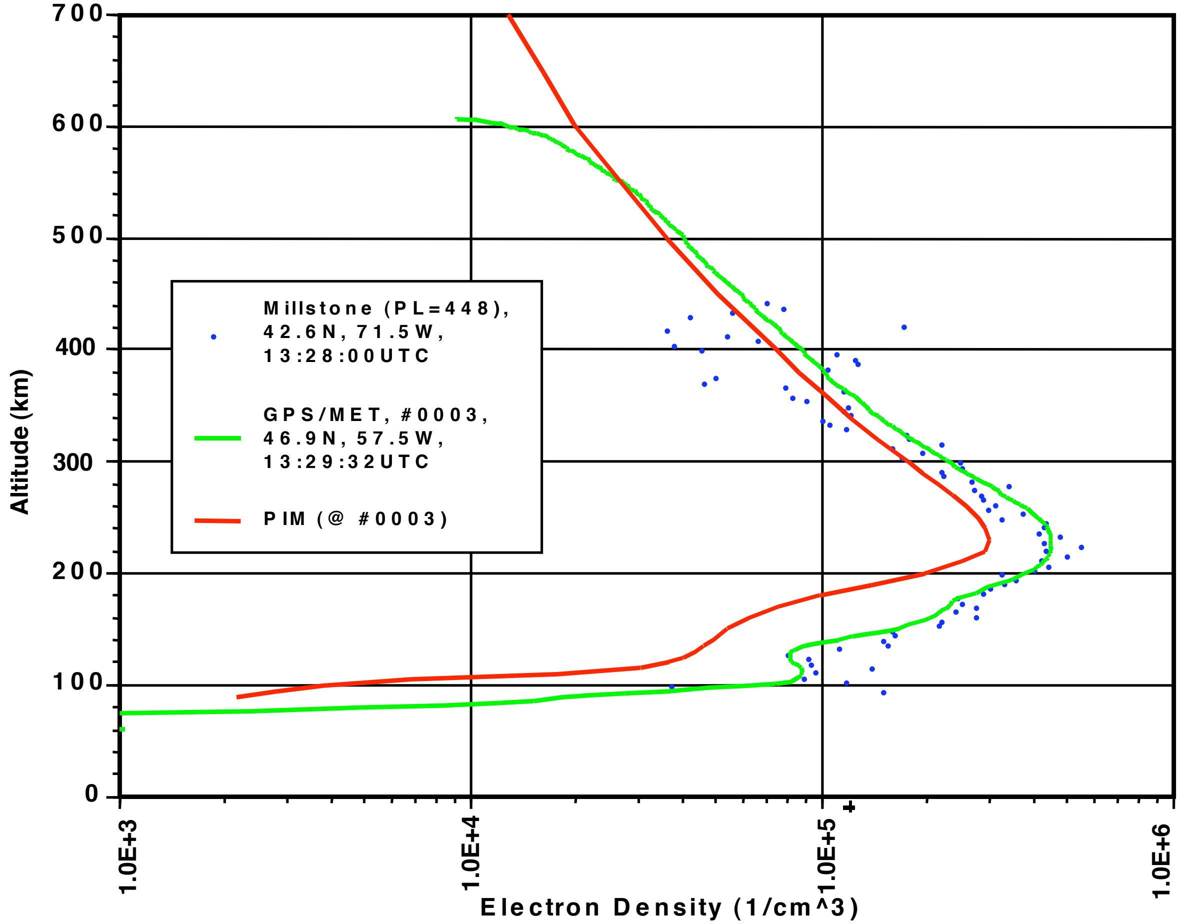
- **Satellite Communication**
  - **specification and forecast of scintillation activity**
    - **e.g., satellite operators, drilling companies**
- **Situational Awareness**
  - **Depressed maximum useable frequencies**
  - **Steep horizontal gradients**
  - **Unusual propagation paths**
  - **Larger positioning errors**
  - **High probability of loss of radio signals**

The Thermosphere and Ionosphere





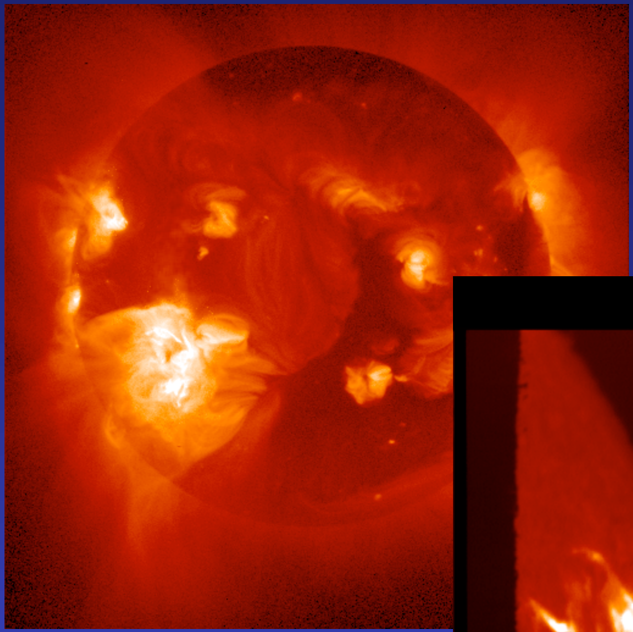
Electron Density Profile



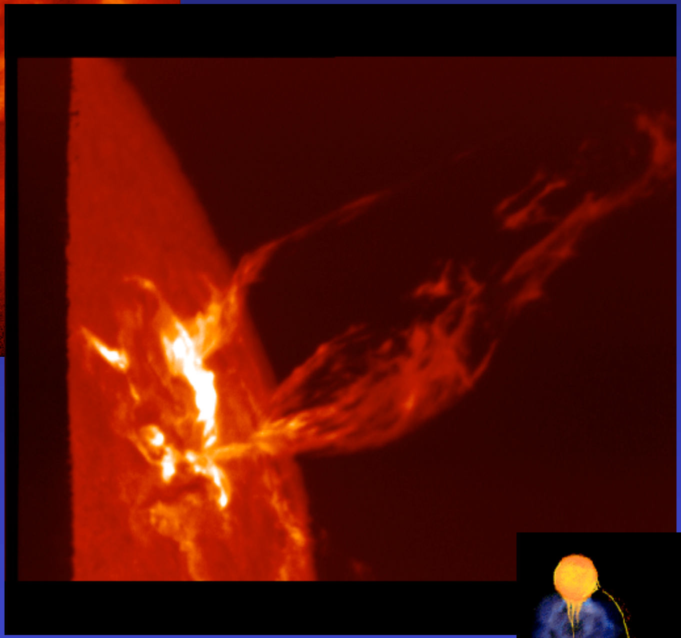
Courtesy:
Chris Rocken
NCAR

Vertical profile of electron density from GPS/MET compared with Millstone Hill incoherent scatter radar observations

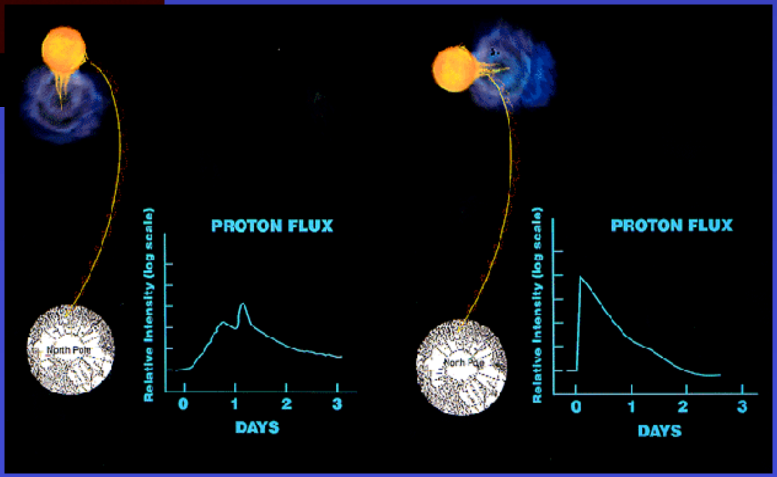
Solar Flares



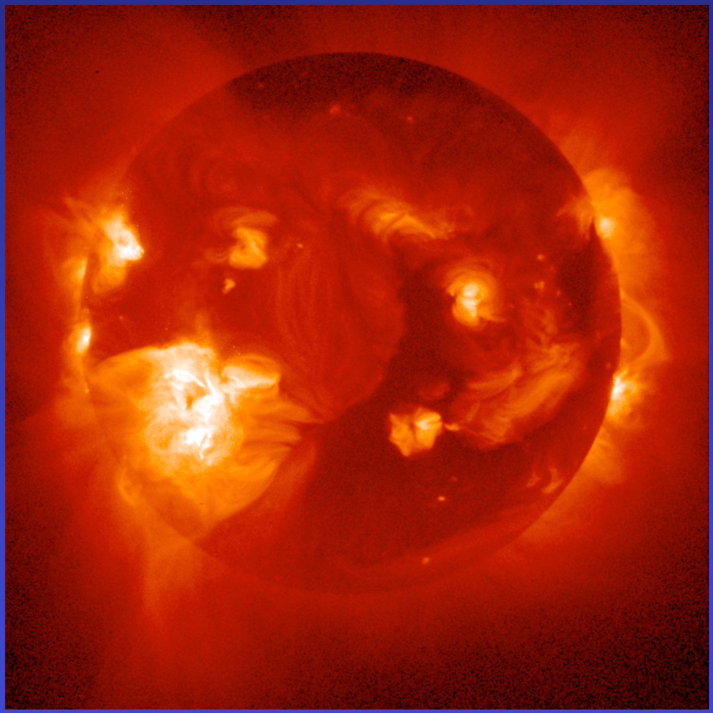
Coronal Mass Ejections



Solar Proton Events



Solar Flares



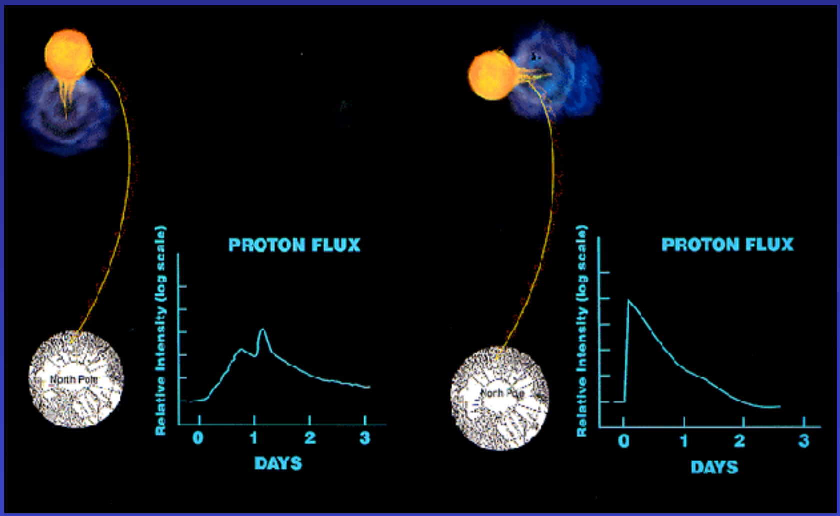
Increased X-ray flux
D-region ionization

Arrival time: 8 minutes
Duration: 1-2 hours

Effects:
- **HF absorption**
- **Disruption of low frequency navigation**
- **GPS navigation**

Users: mariners, coast guard, HF frequency managers, commercial aviation, military

Solar Proton Events



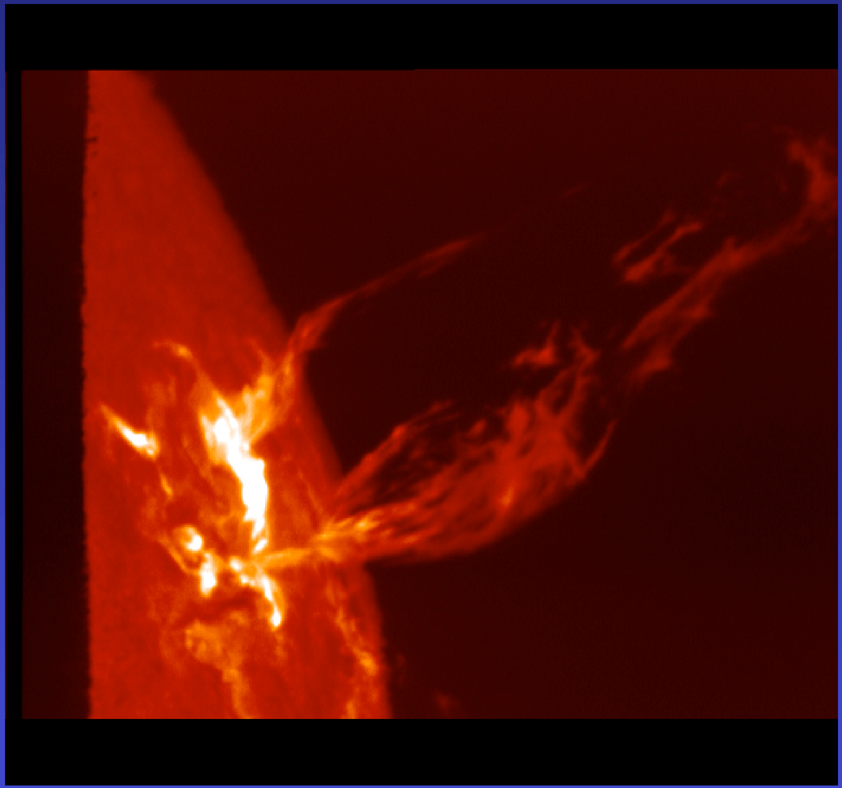
High energy particles

Arrival time: 15 mins to few hours
Duration: several days

Effects:
- Single event upsets (SEU)
- Deep dielectric charging
- **HF absorption**
- **Low frequency navigation outage**
- Radiation hazard

Users: satellite operators, HF frequency managers, commercial aviation, mariners, astronauts, …..

Coronal Mass Ejections

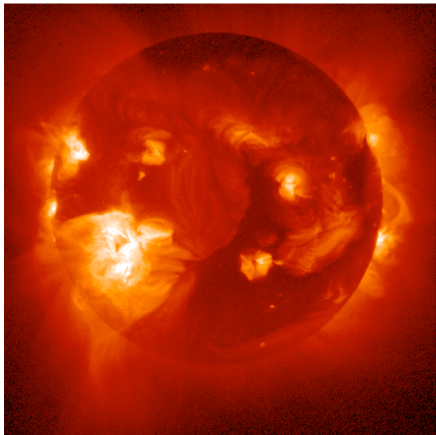


Geomagnetic Storm

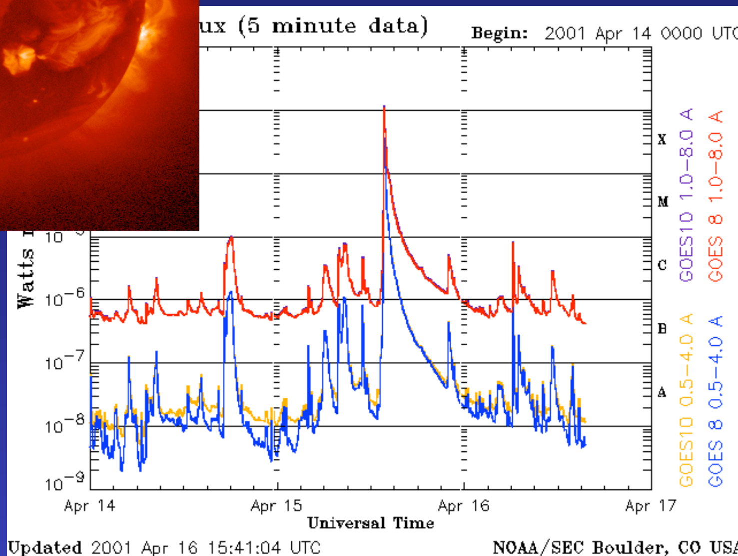
Arrival time: 1-3 days
Duration: 1-2 days

Effects:
Spacecraft charging
Satellite drag
HF Communications
GPS Navigation
Induced currents

Users: Power companies, satellite operators, HF frequency managers, FAA, military, GPS,...



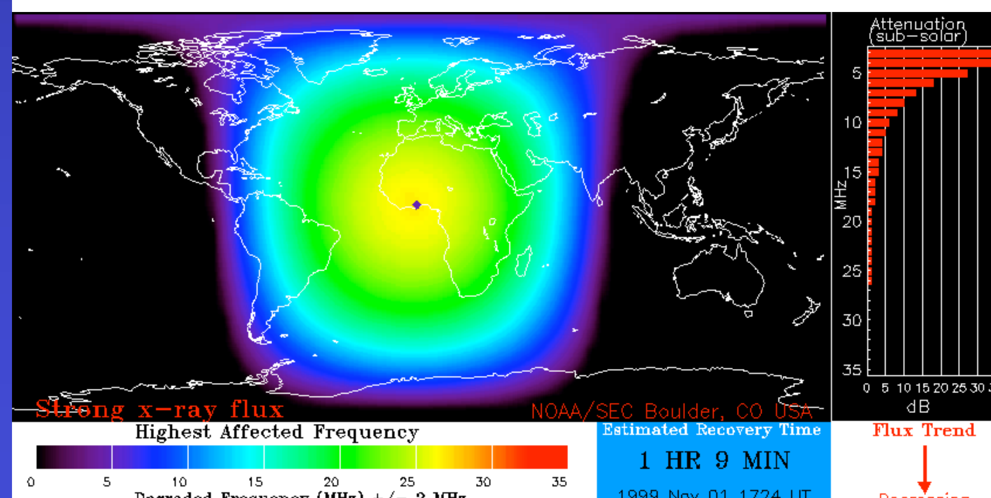
GOES



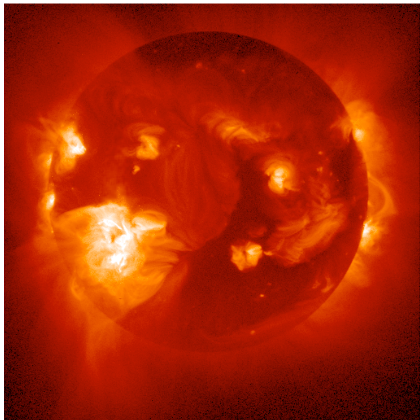
Solar X-rays

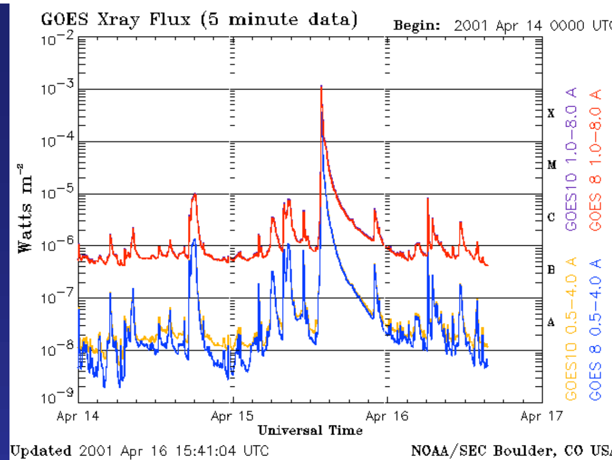
Effect of Solar X-rays on D-Region and HF Propagation.

- **D-Region Absorption Product based on GOES X-Ray Flux (SEC Product)**
  - **The map shows regions affected by the increased D-region ionization resulting from enhanced x-ray flux during magnitude X-1 Flare**

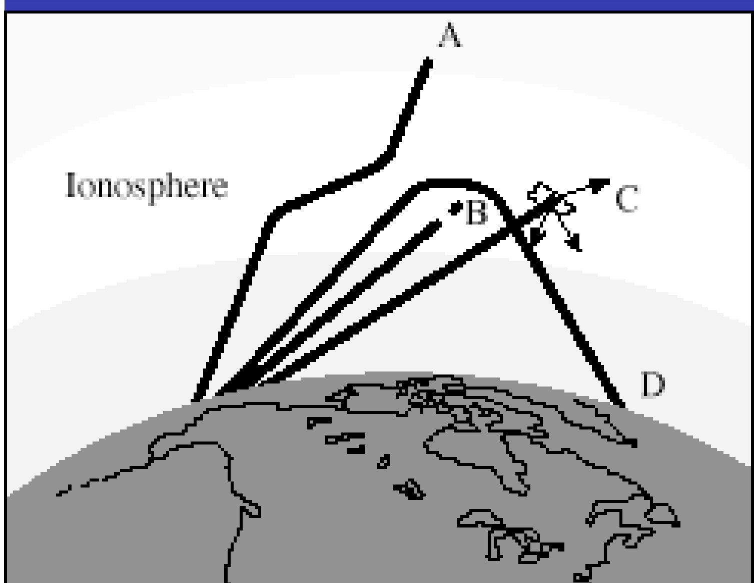


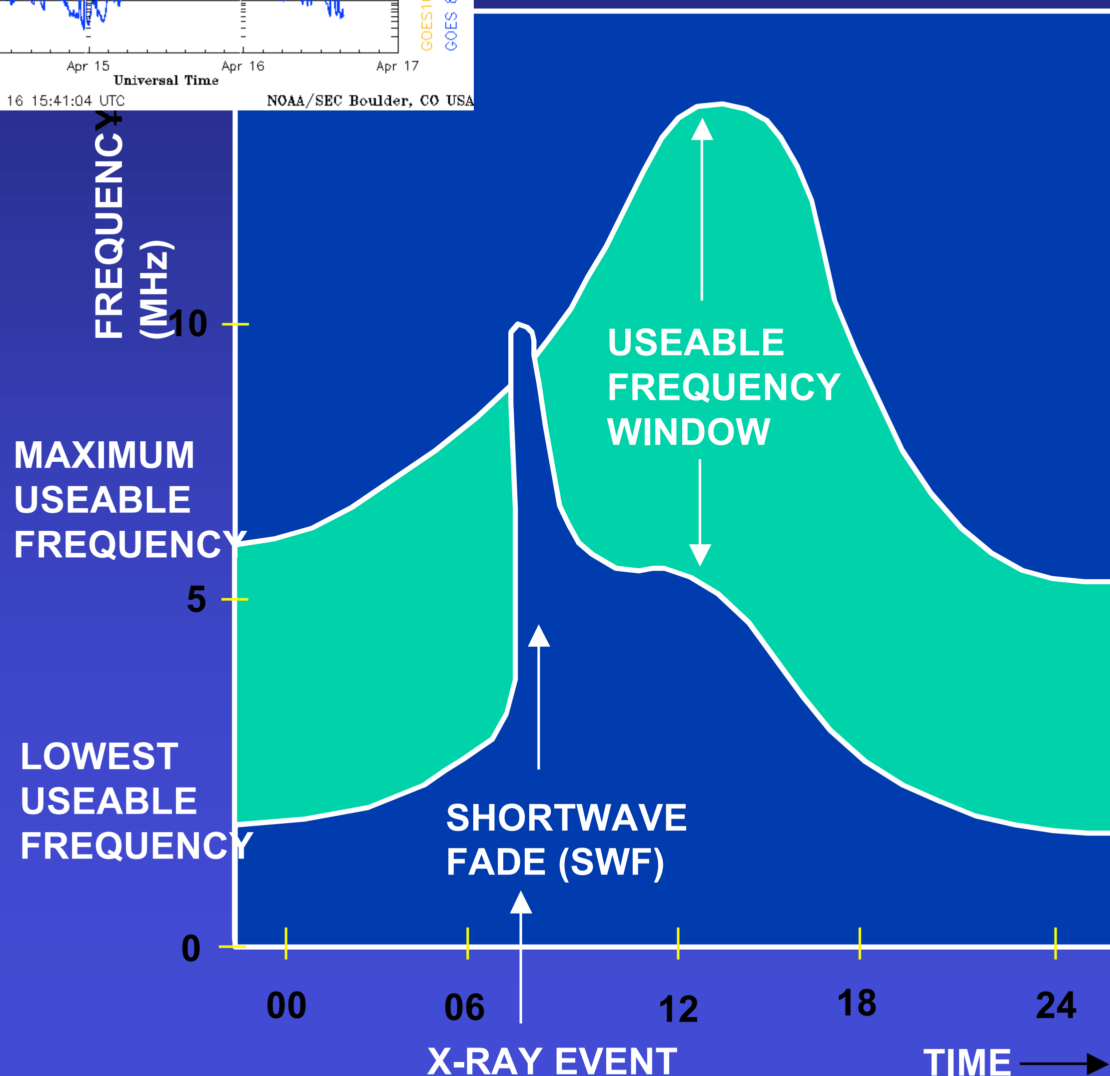
Dayside response
Zenith angle dependence
Time scale follows source



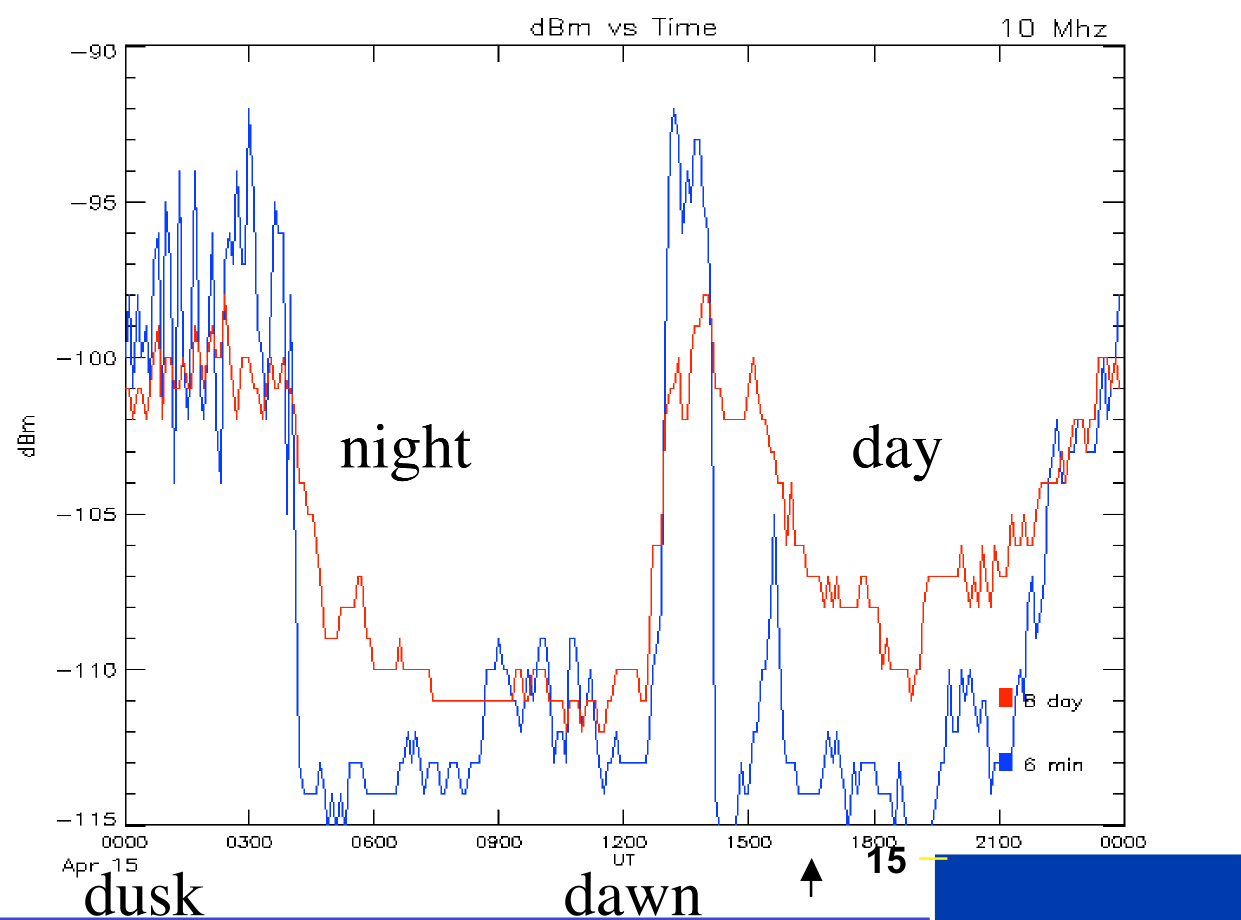


Solar Flares:
HF Absorption
Radio Blackout

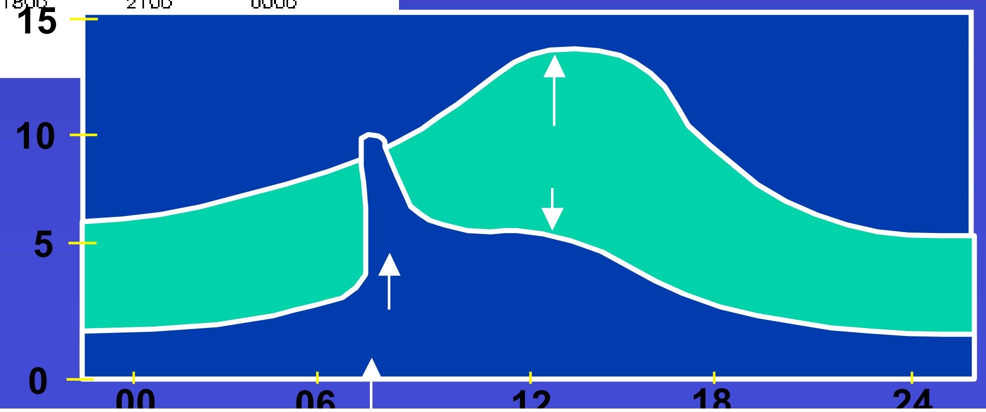




Radio Wave Propagation
Fort Collins, CO to Cedar Rapids, ID



Signal Strength at 10 MHz



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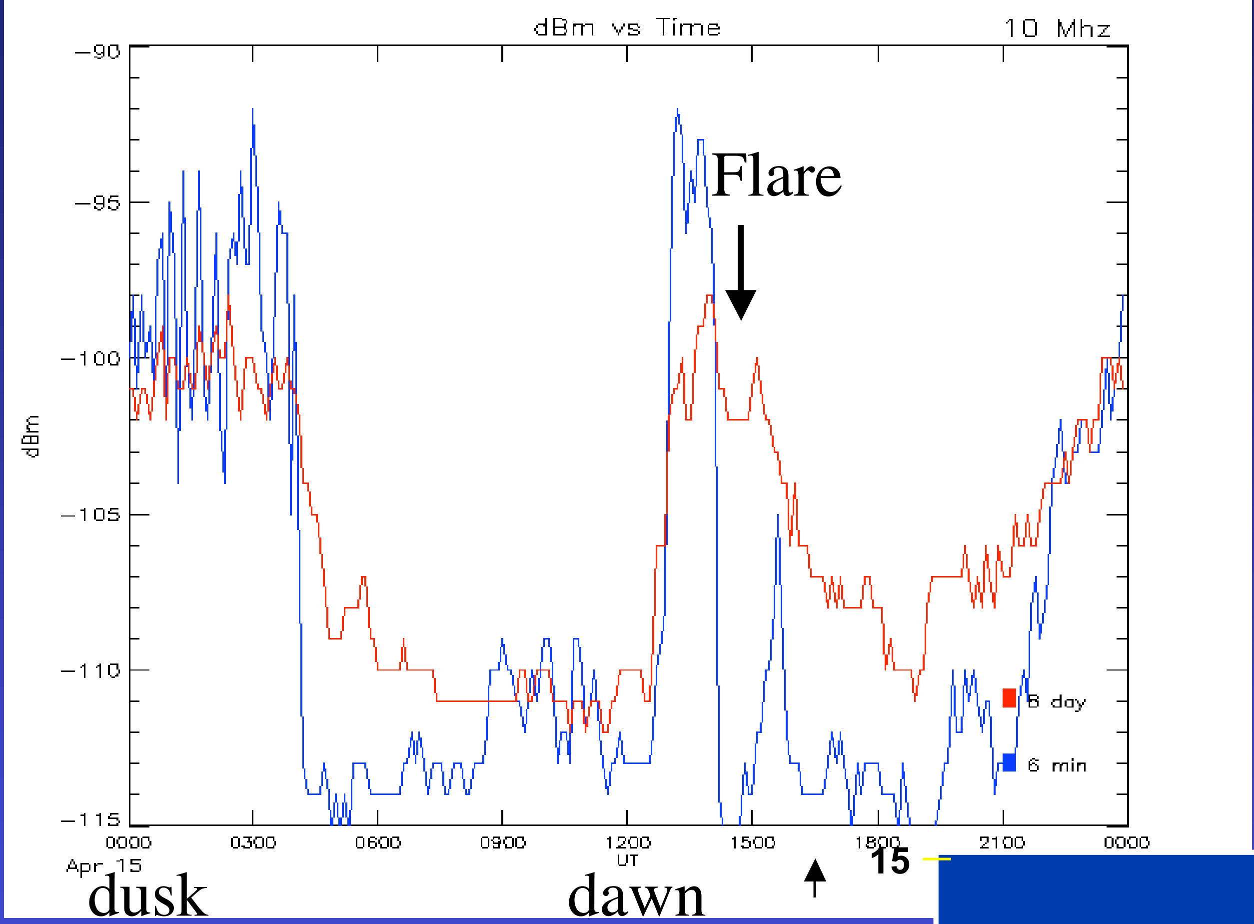

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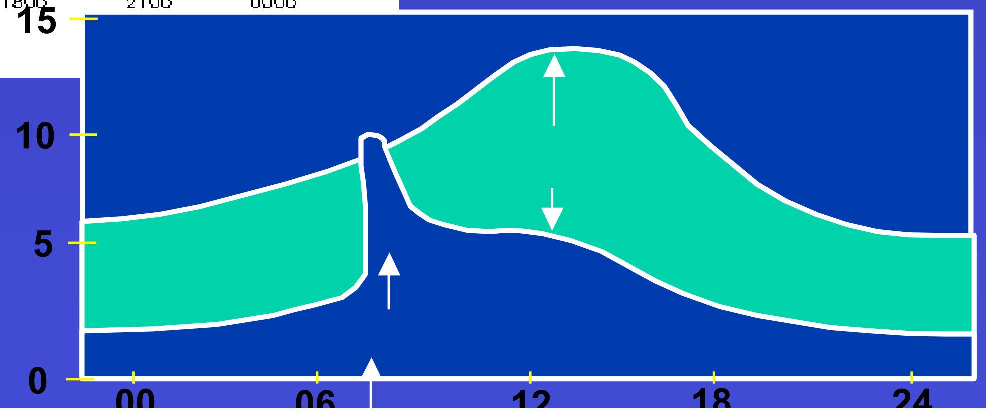
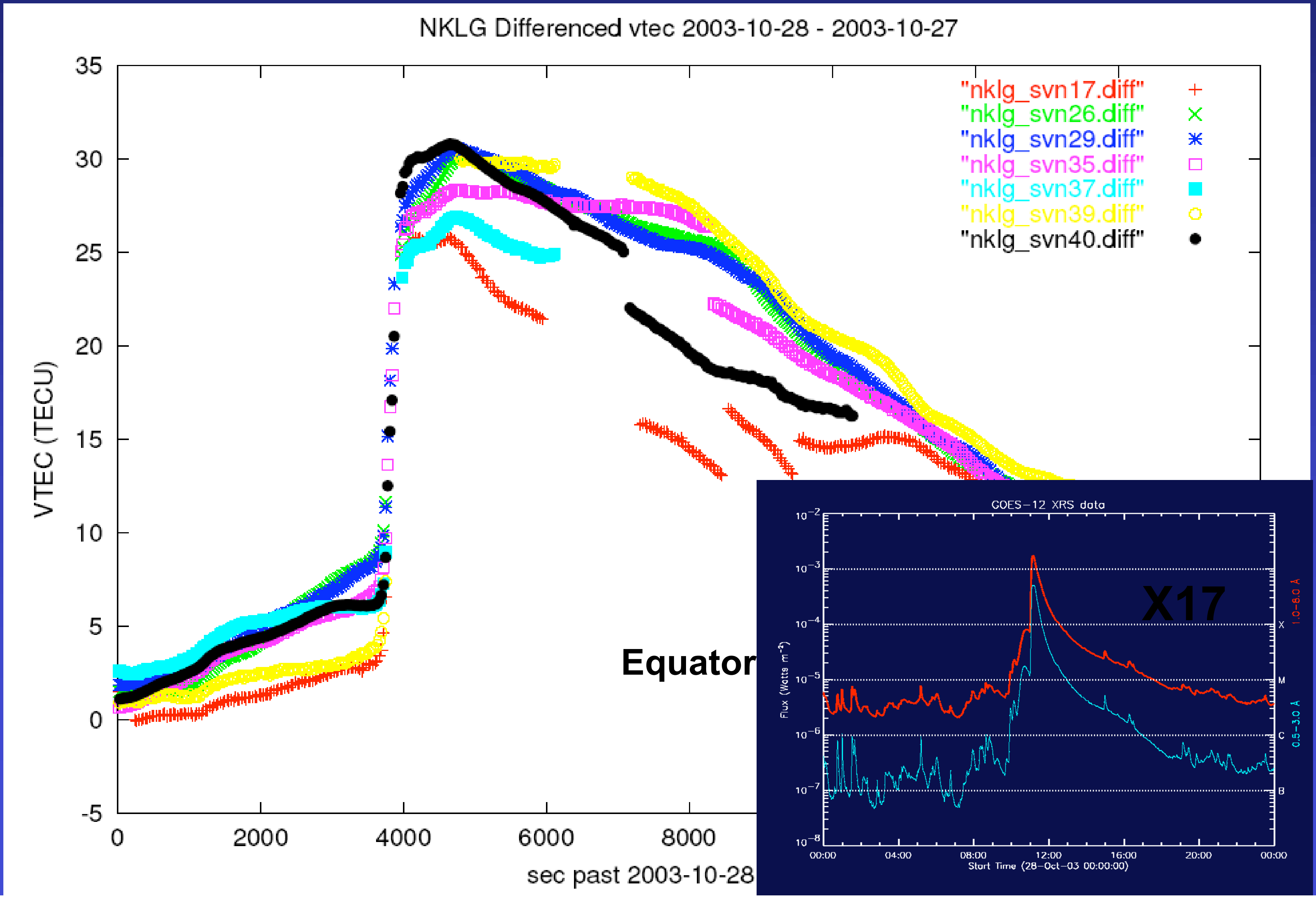
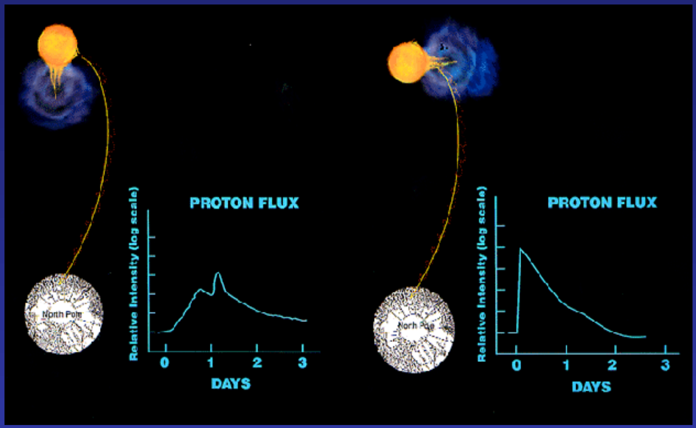
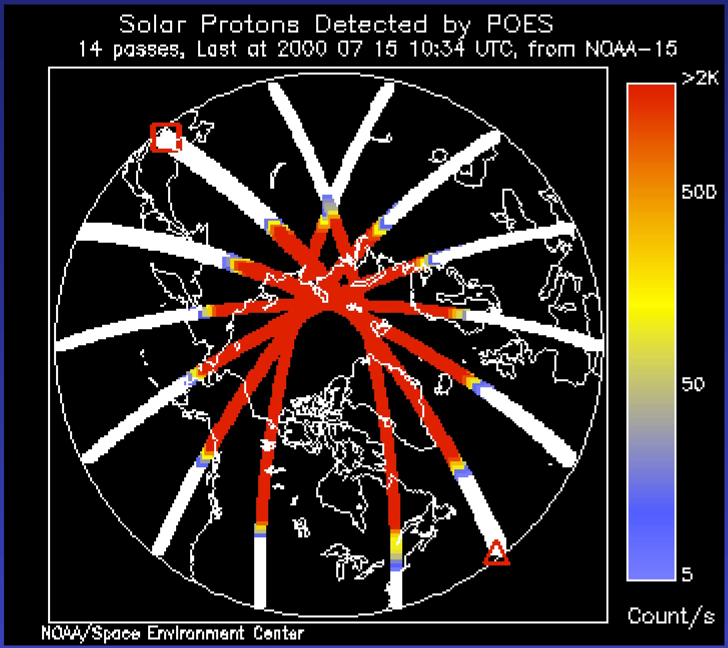


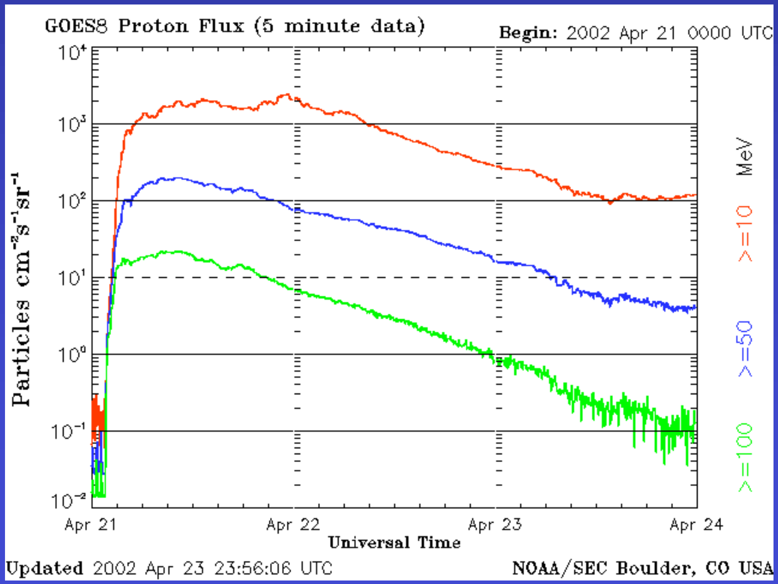
TEC GPS Differential Phase measurements

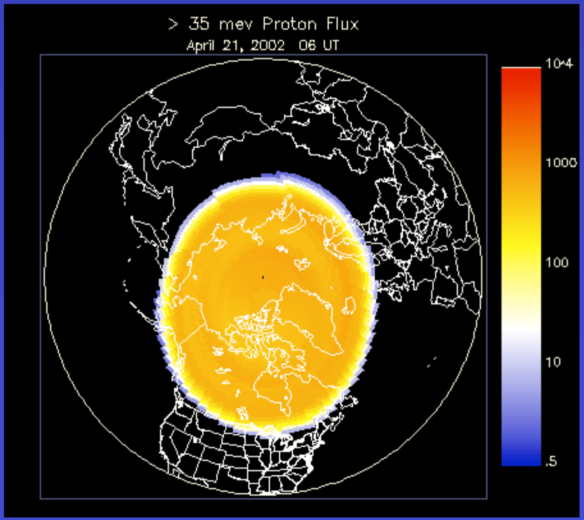


Solar Protons



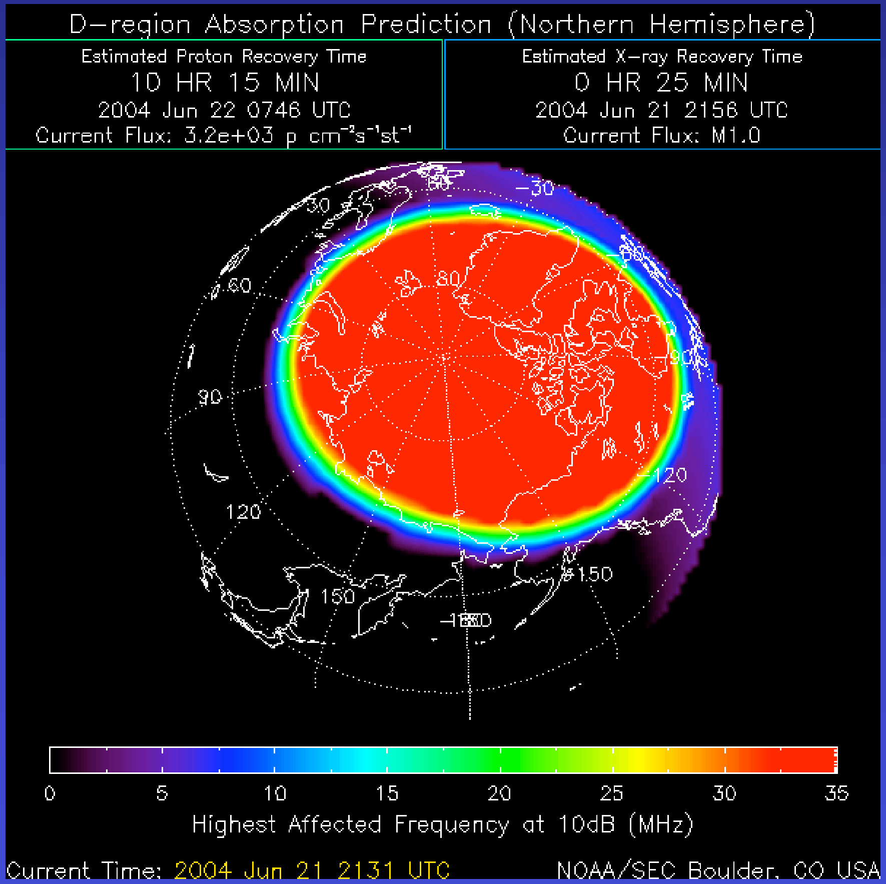


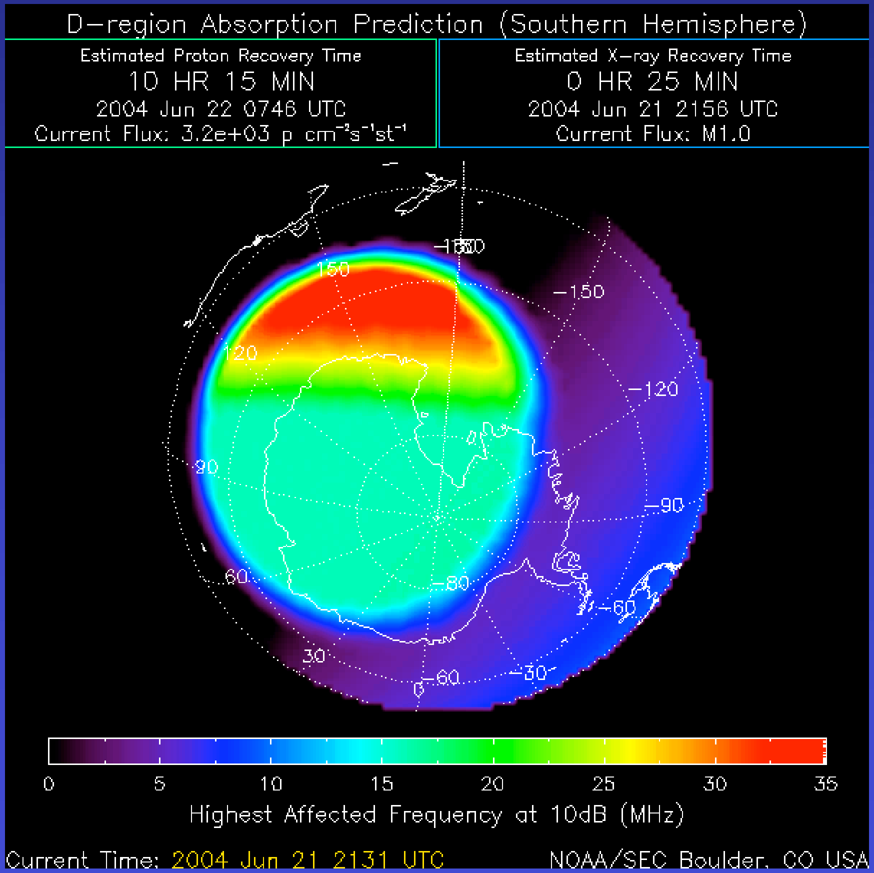




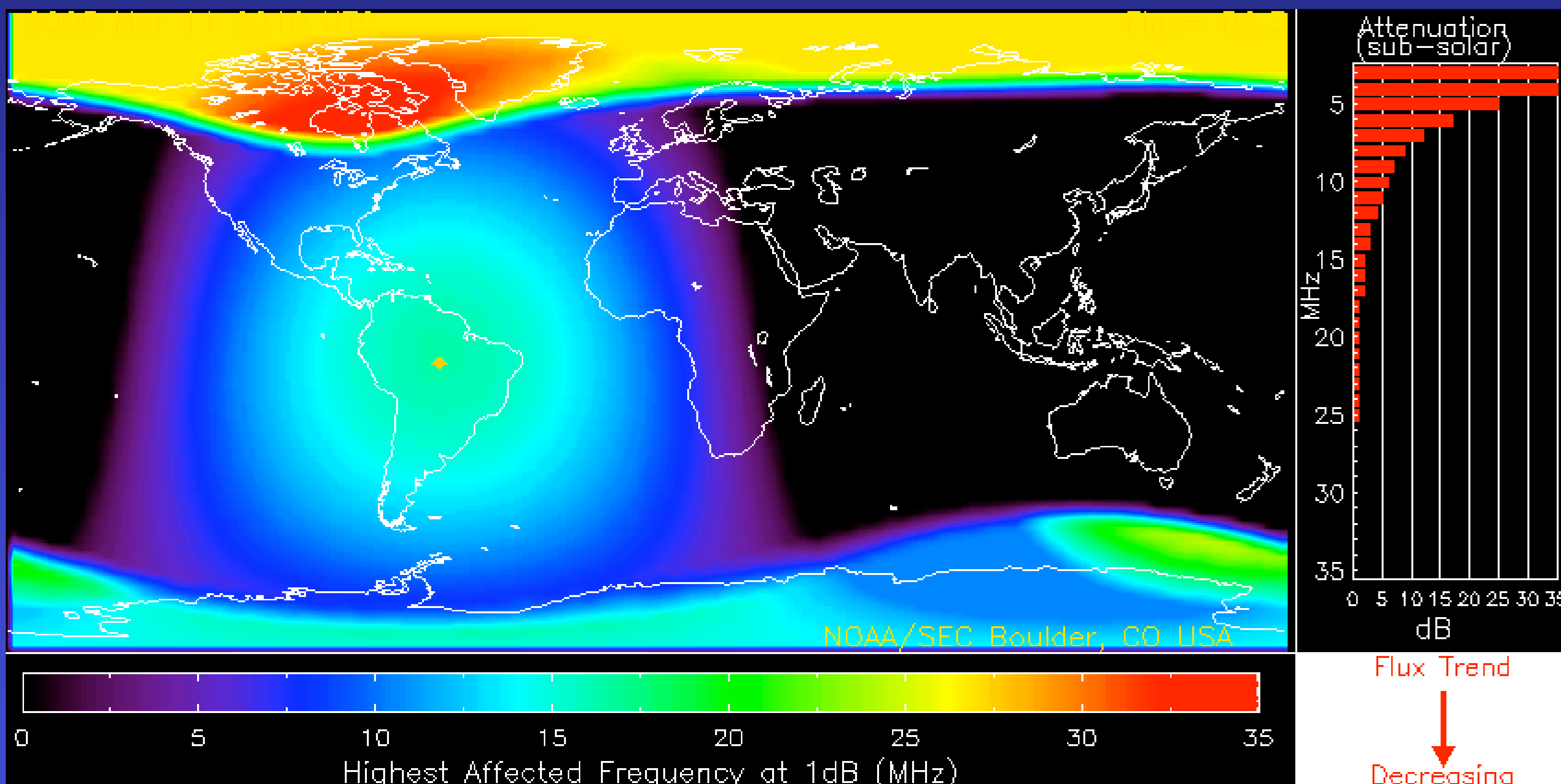
PCA depends on solar illumination

O_2 - e^- attachment process in the D-region

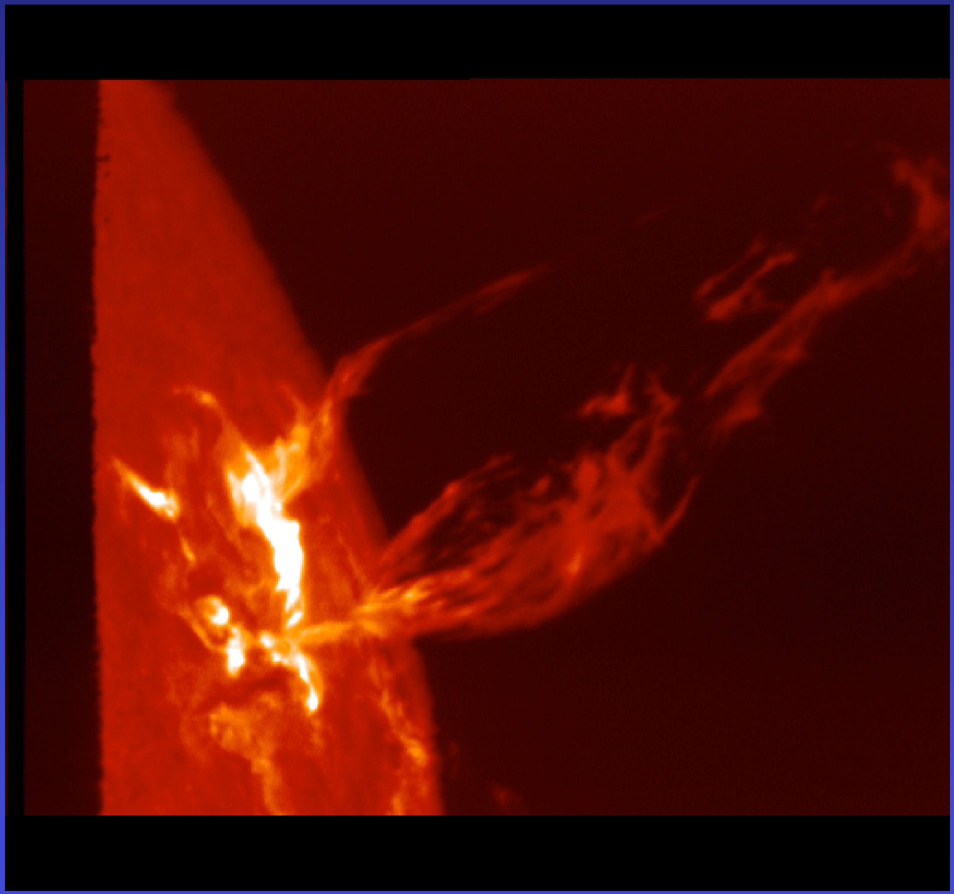




Combined X-ray and PCA



Coronal Mass Ejection

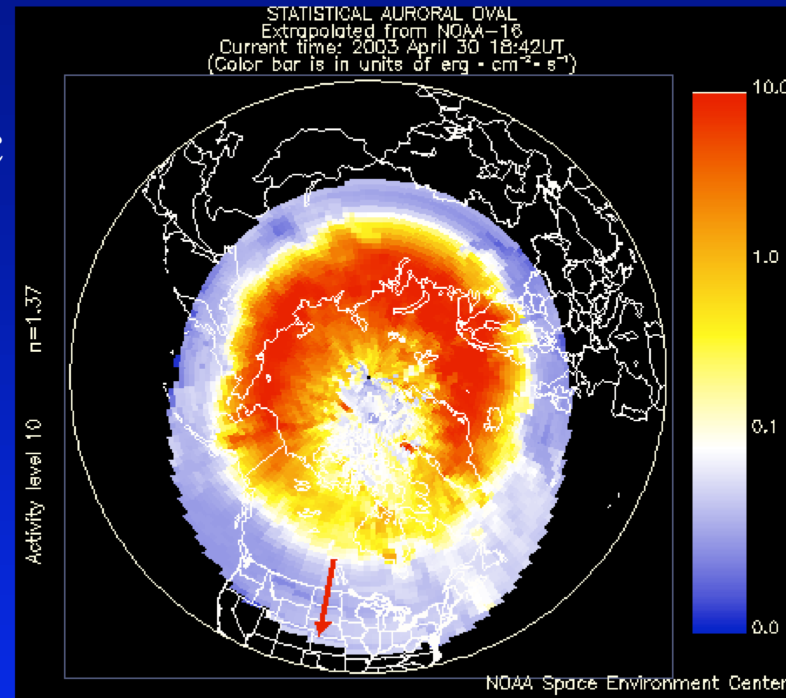


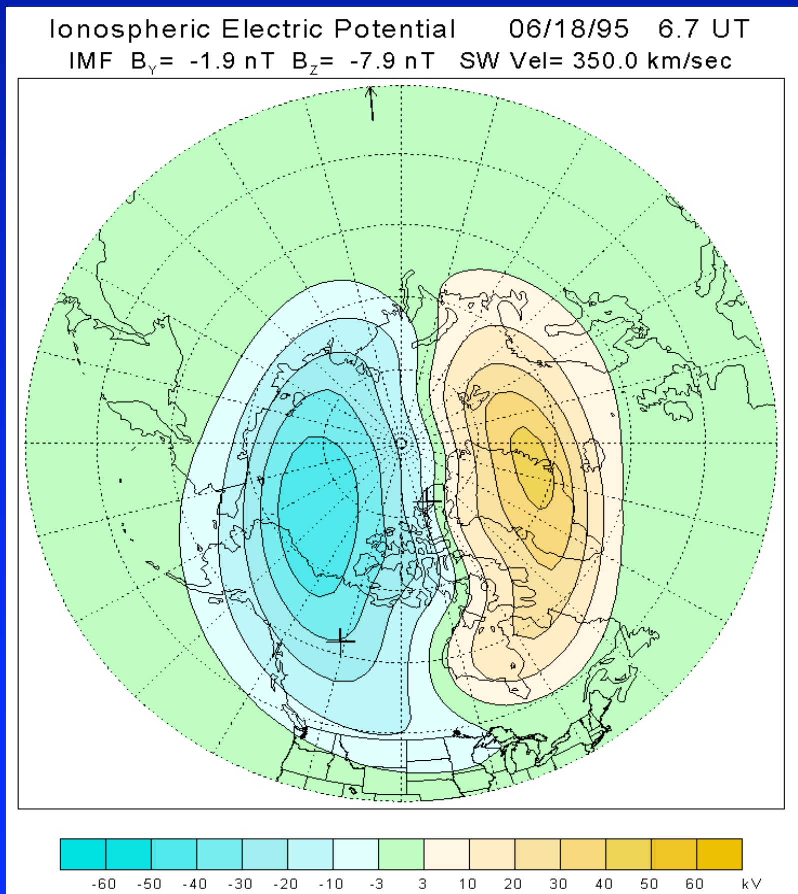
A single eruption can release a billion tons of material into the solar wind

Speeds can exceed several million miles per hour

Energetic particles accelerated by shocks cause bright flashes in the image (and in DNA!)

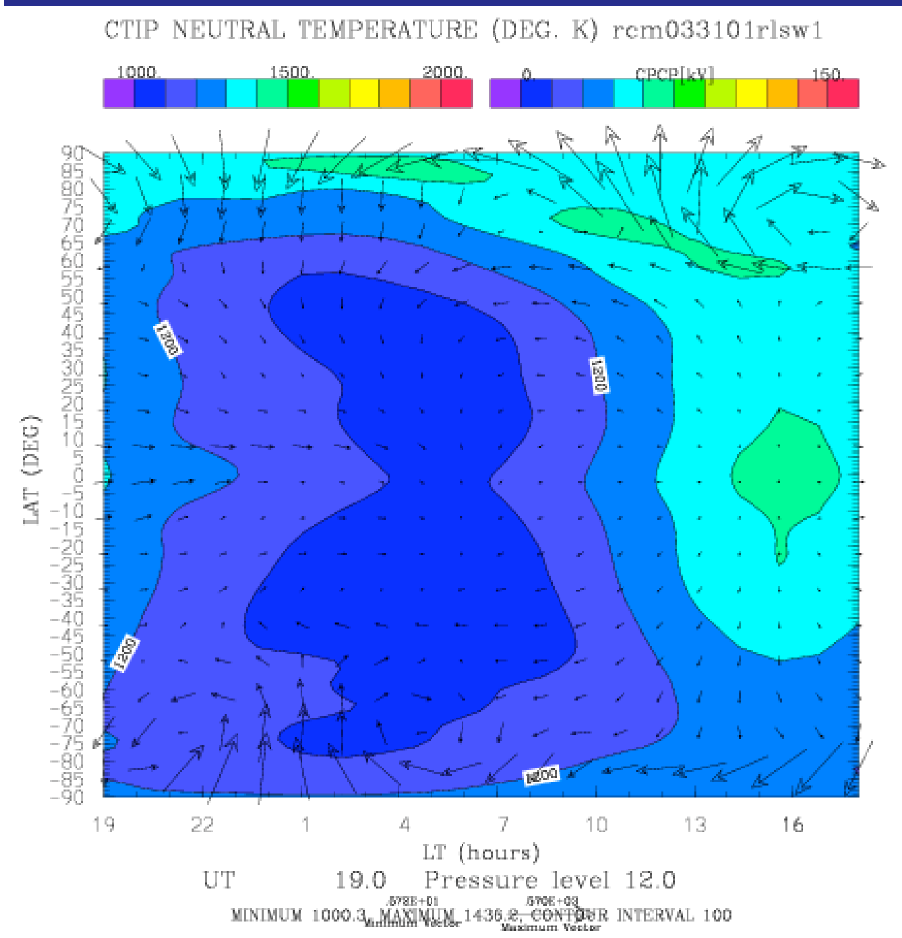
Increased energy input to the upper atmosphere: auroral particle precipitation and magnetospheric convection electric field

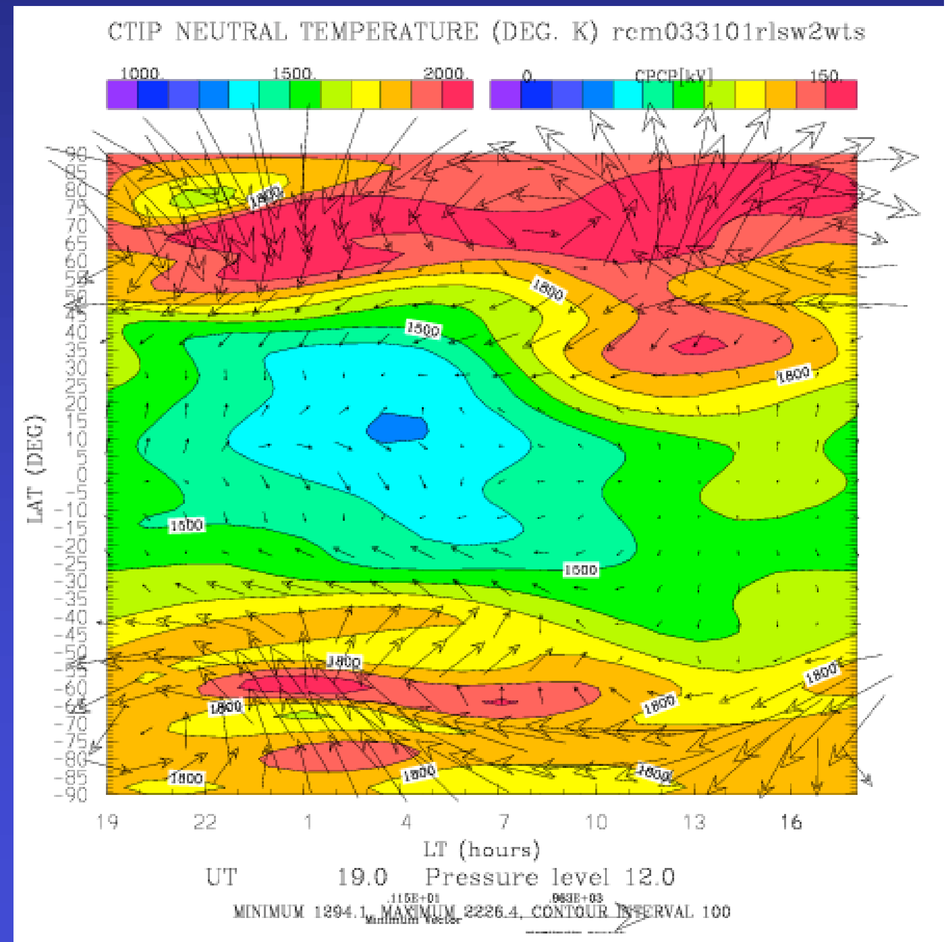


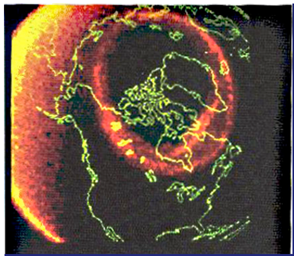


E_{pc} 10 - 300 kV in minutes

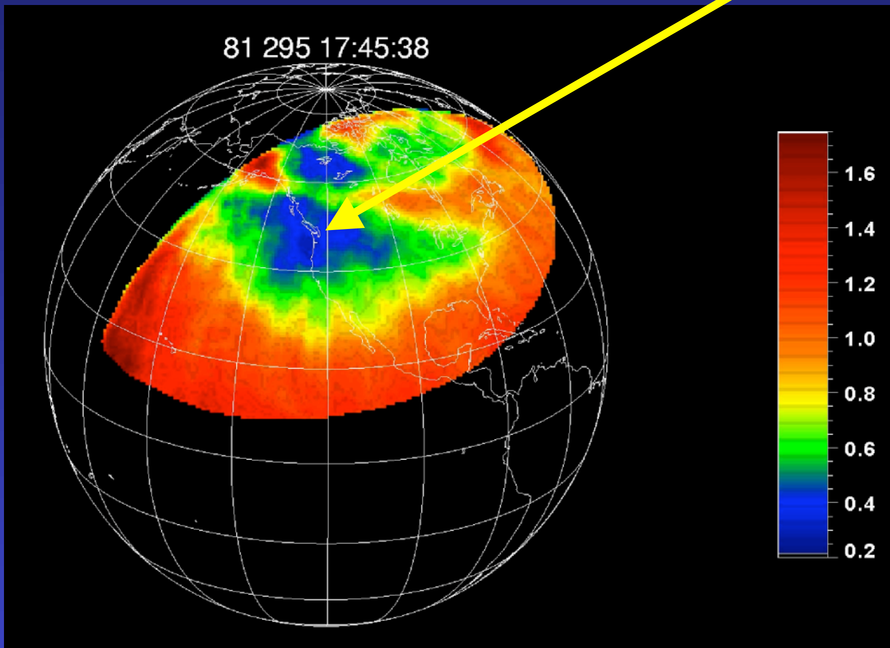
Large temperature and circulation changes in the upper atmosphere

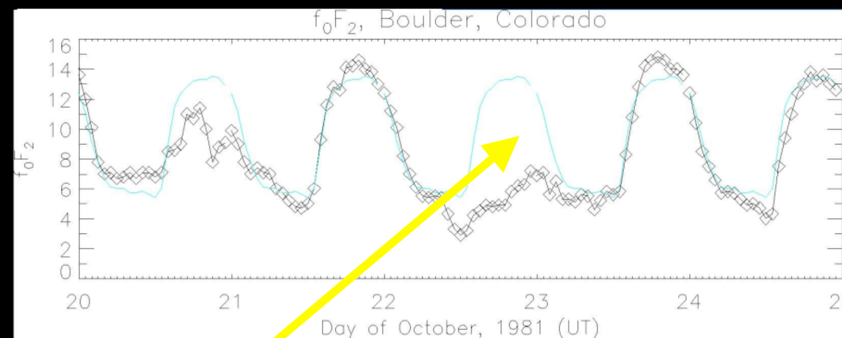




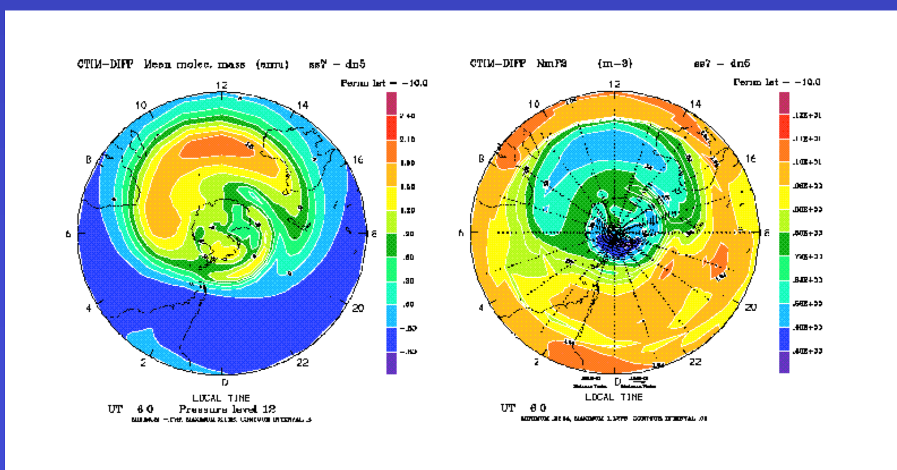


Oxygen Depletions Imaged from Space



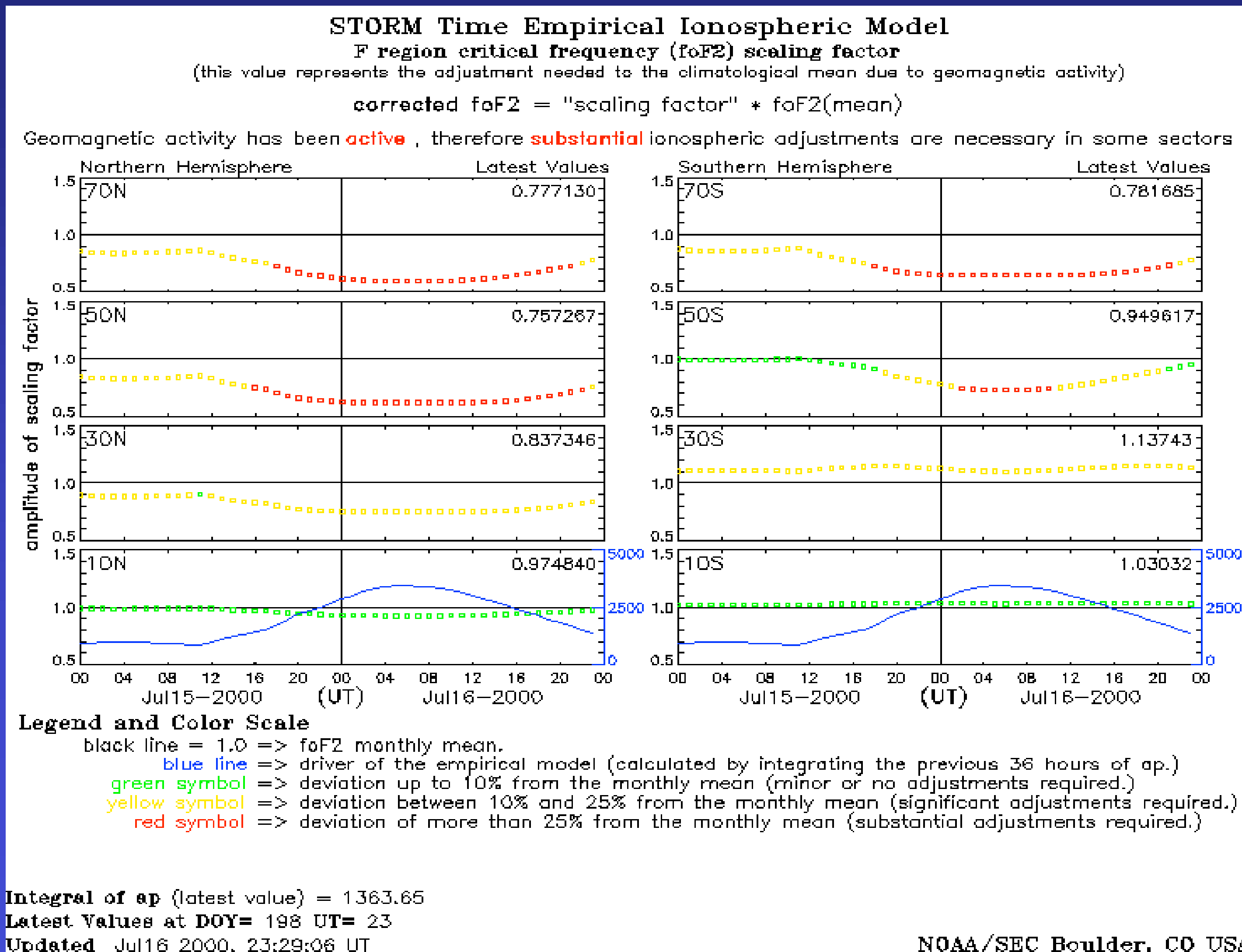


wipe out ionosphere

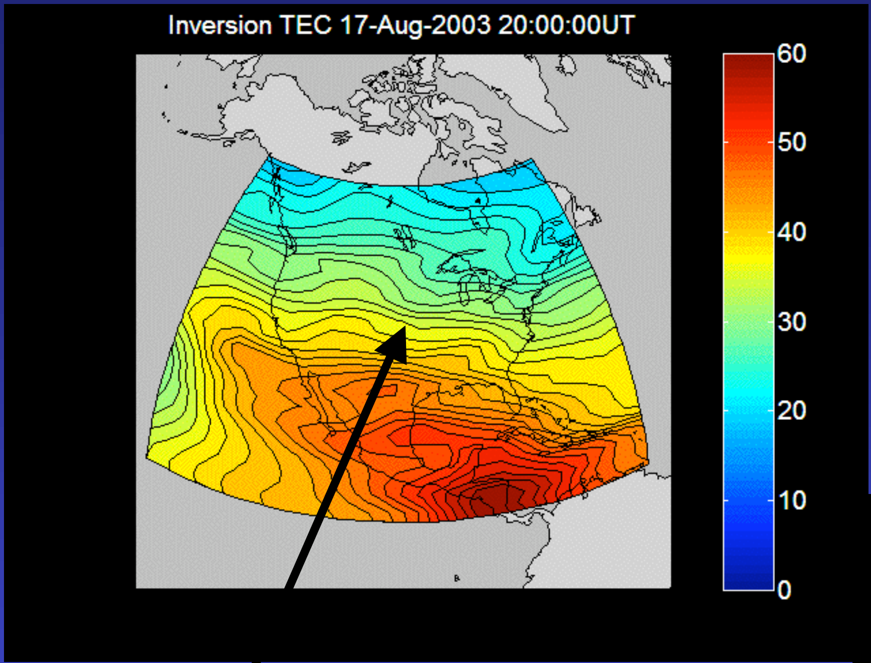


Strong correlation between O/N_2 and ionospheric depletions

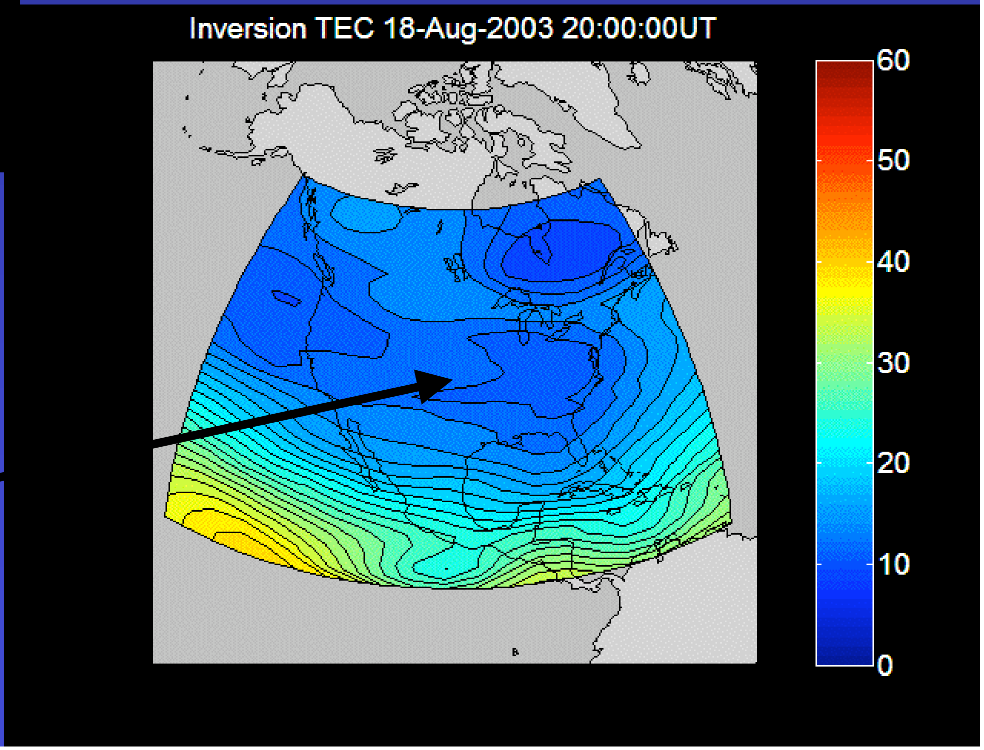
STORM product



Ionospheric TEC using data assimilation techniques



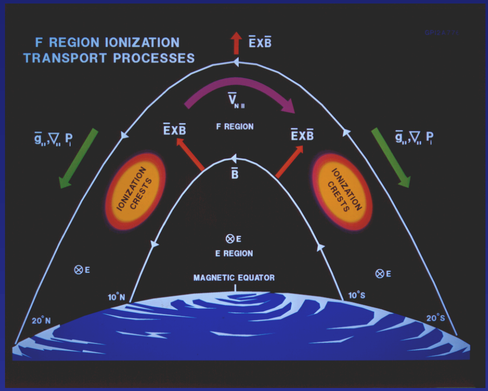
The geomagnetic storm on Monday August 18th 2003 wiped out the normal daytime peak in TEC and electron density over North America

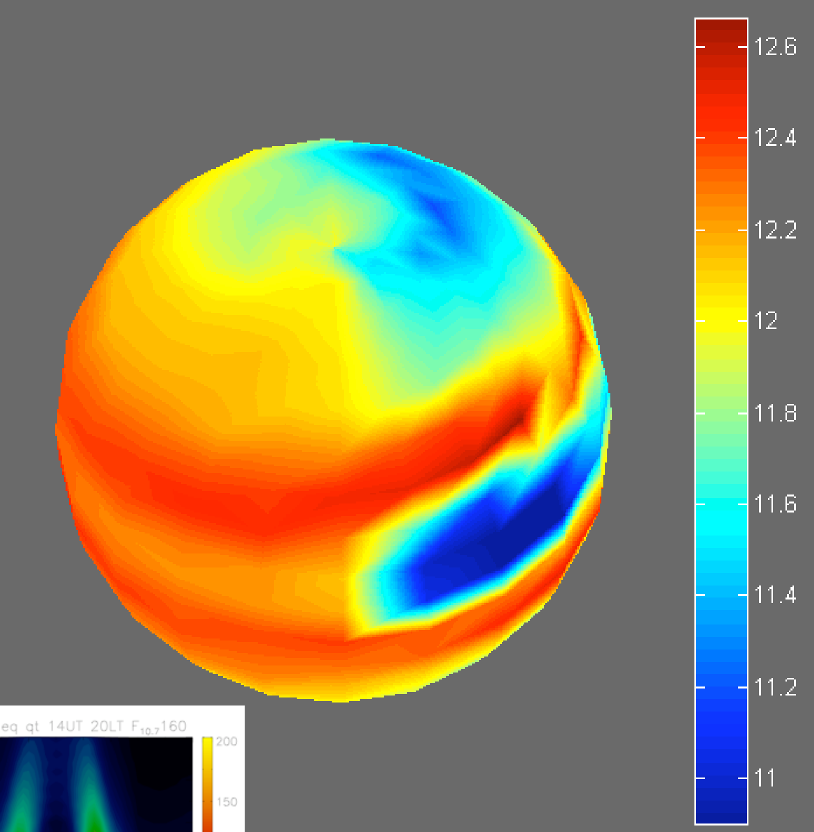


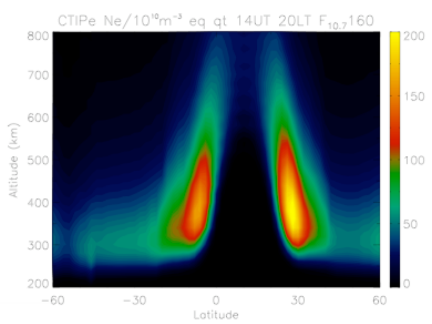
Normal quiet-day maximum on August 17th

Ionospheric depletion on the 18th during the storm

Electrodynamics





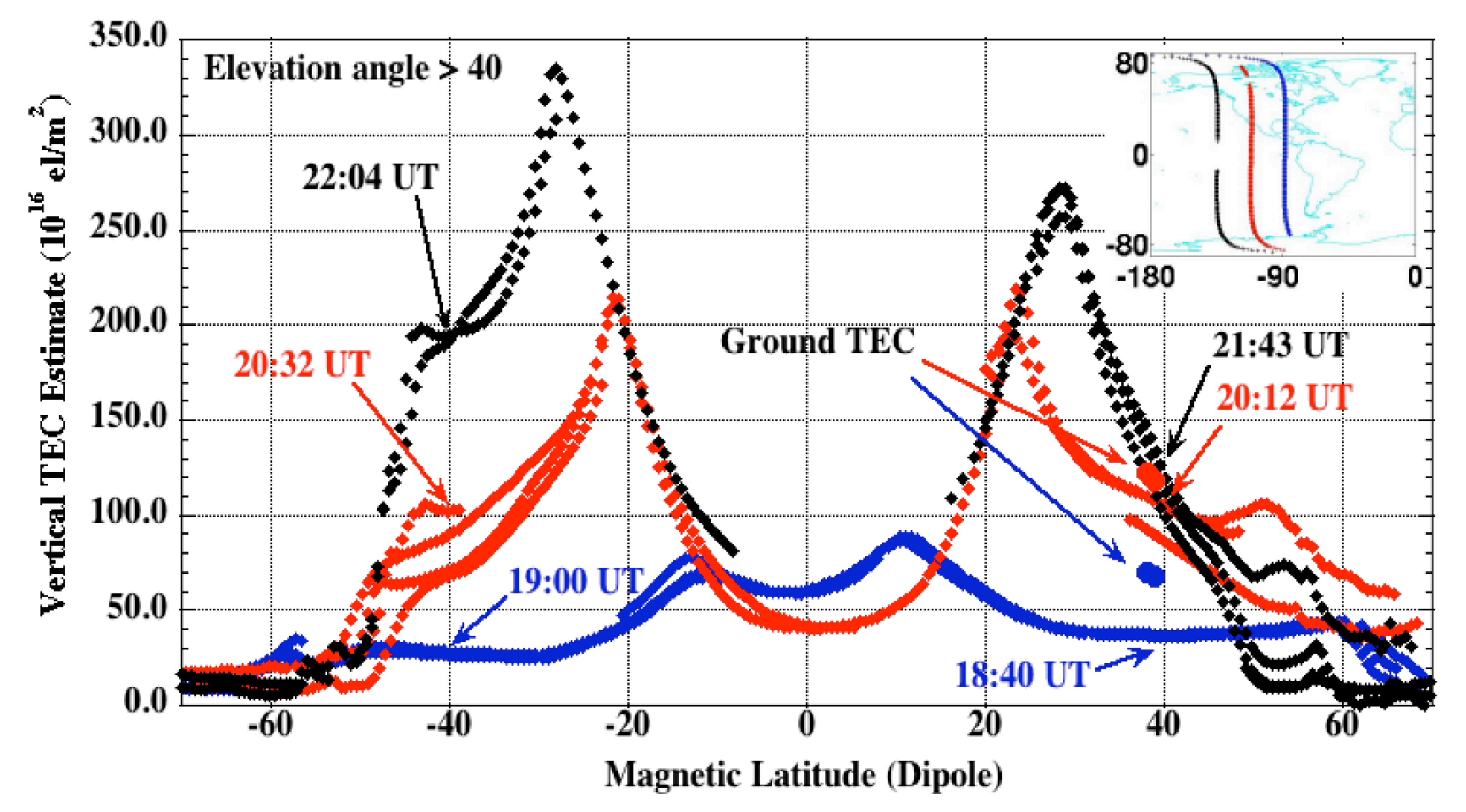


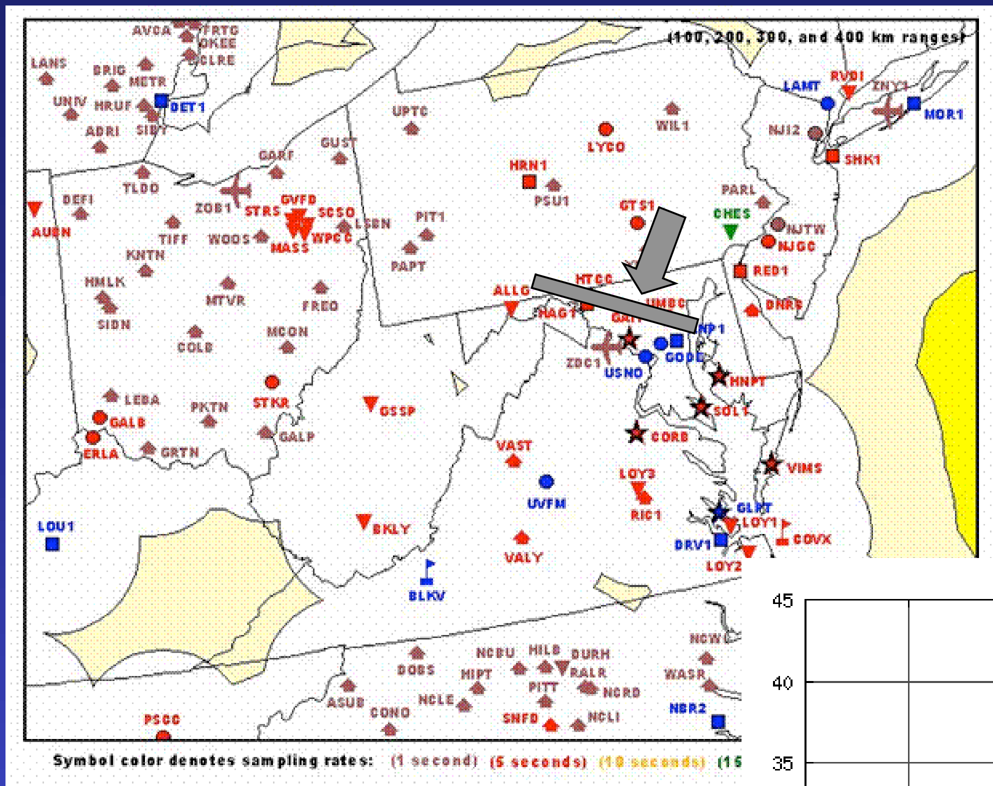
•Penetration and dynamo electric fields can strengthen the EIA and deepen equatorial holes.

•Ring current polarization electric fields can transport ionospheric plasma and produce troughs

•Huge gradients in plasma density ensue.

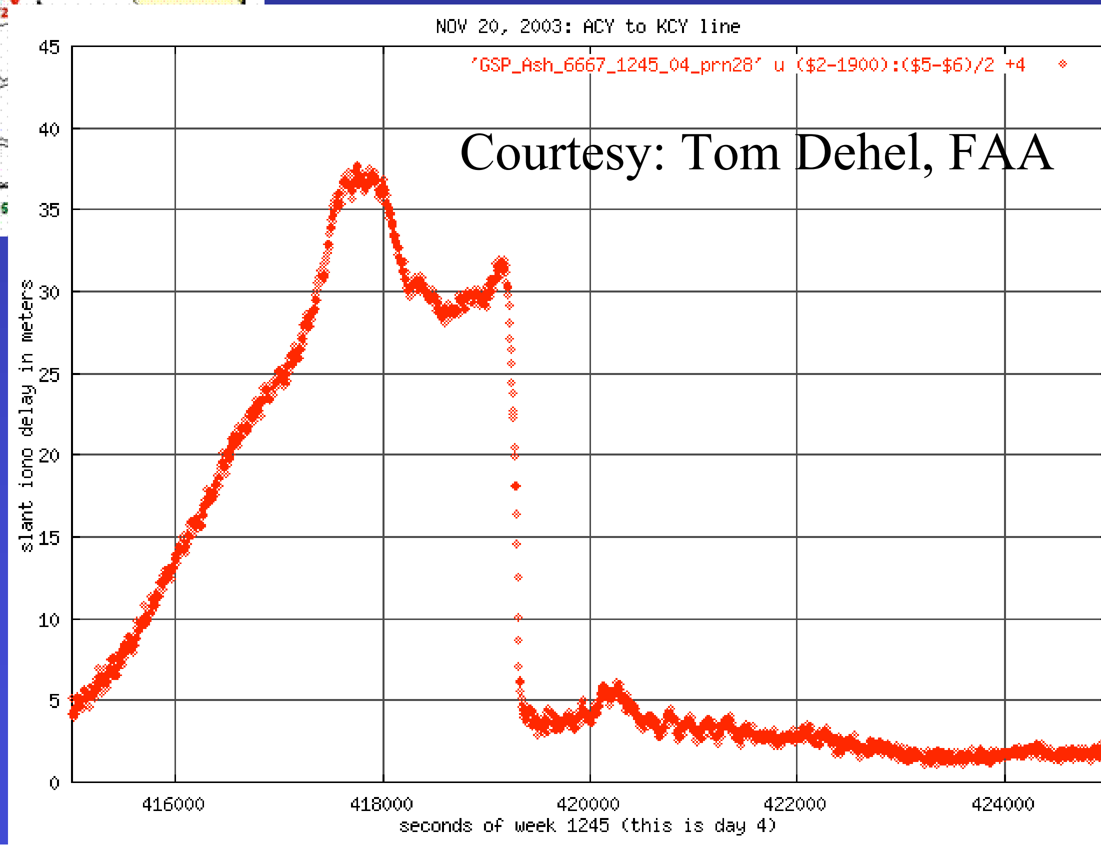
CHAMP (400 km) OSEC: Halloween
Mannucci et al. 2005





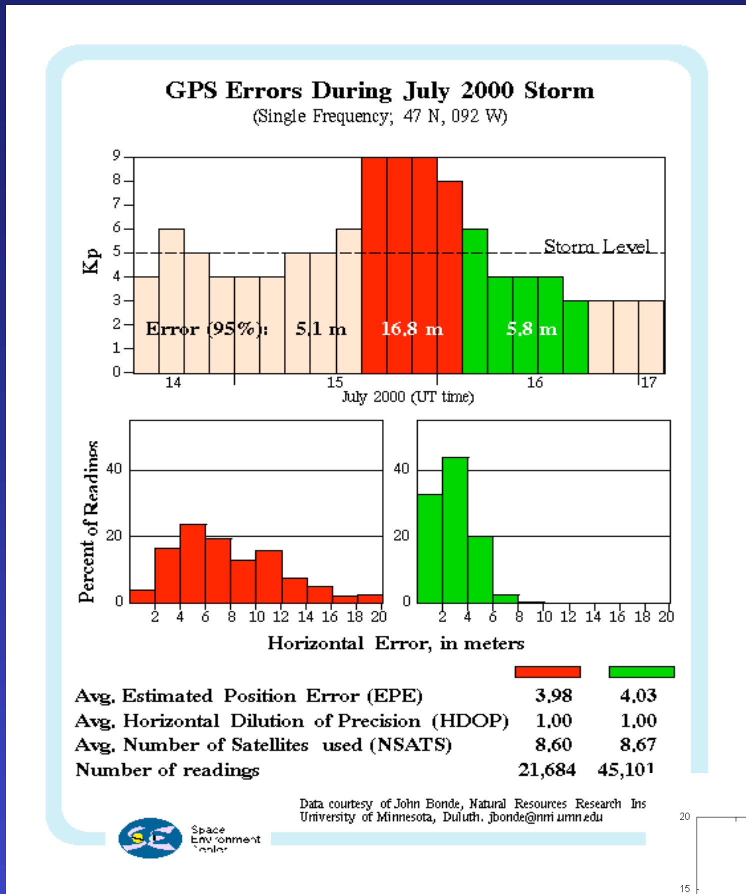
One of the challenges:

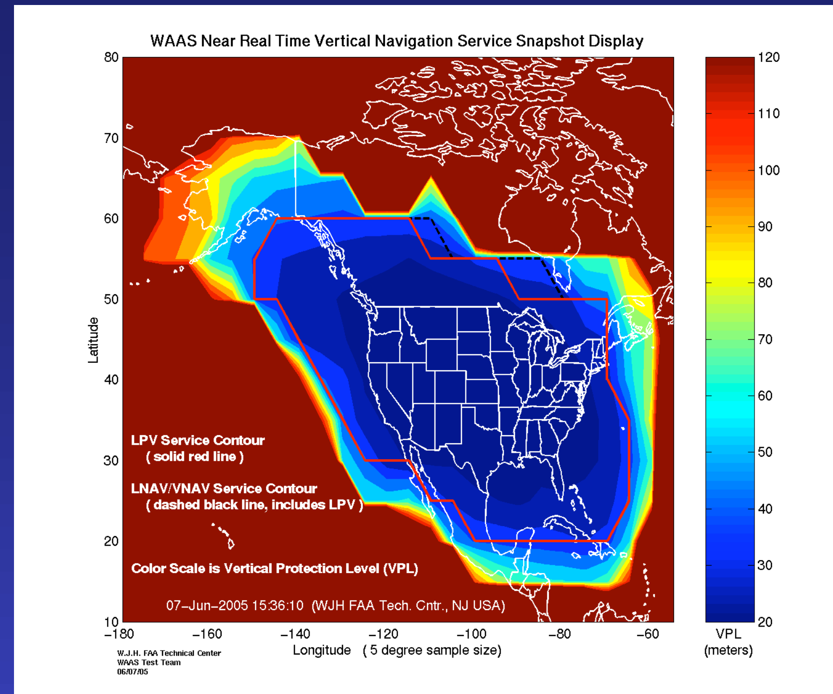
October 29th, 2003 stationary “walls” of TEC compromise integrity of LAAS



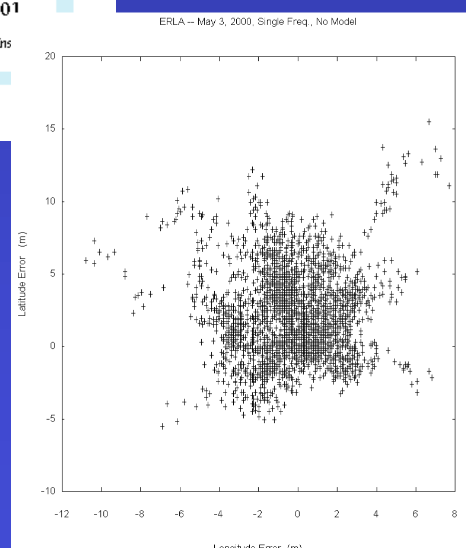
Courtesy: Tom Dehel, FAA

TEC “walls”:
130 TEC units over 50 km
20 m of GPS delay;
walls move 100 to 500 m/s





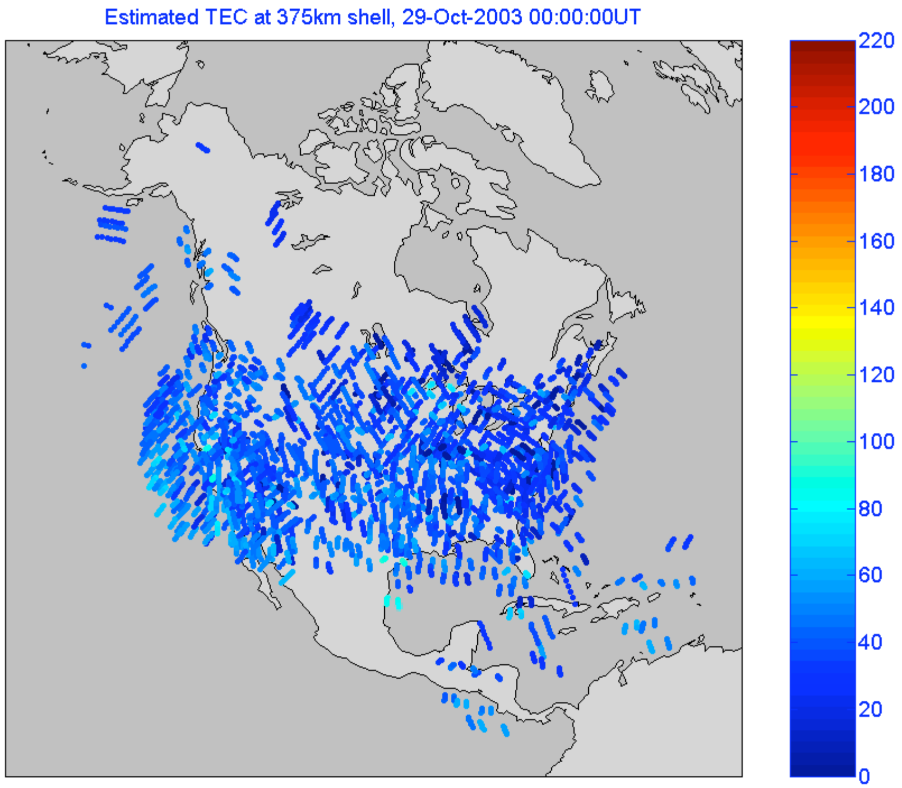
High correlation between disruption of WAAS availability and TEC gradients

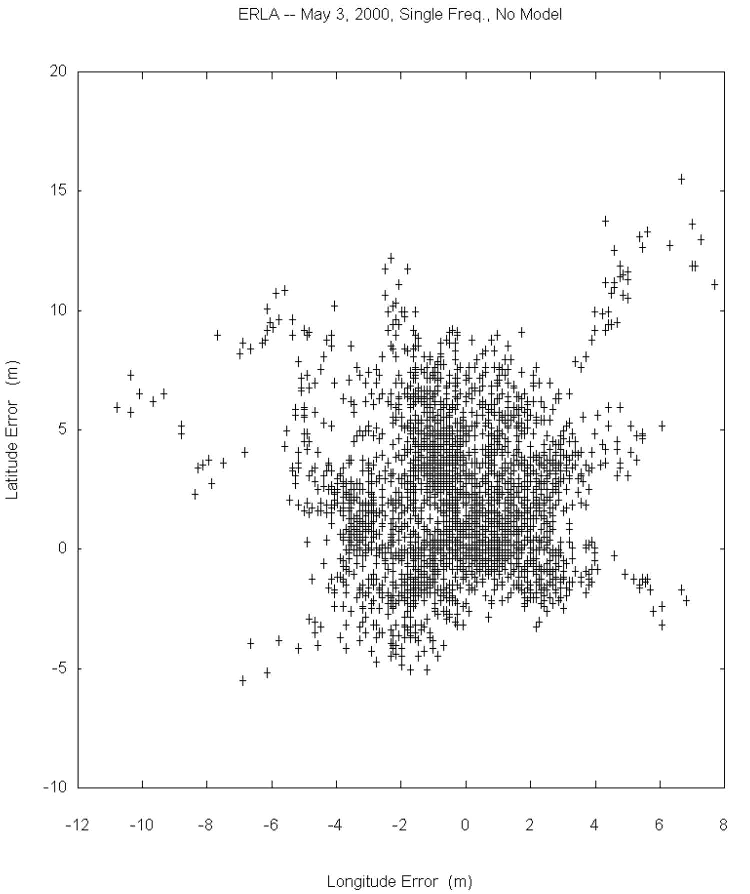


•Steep TEC gradients increase GPS positioning errors

5m

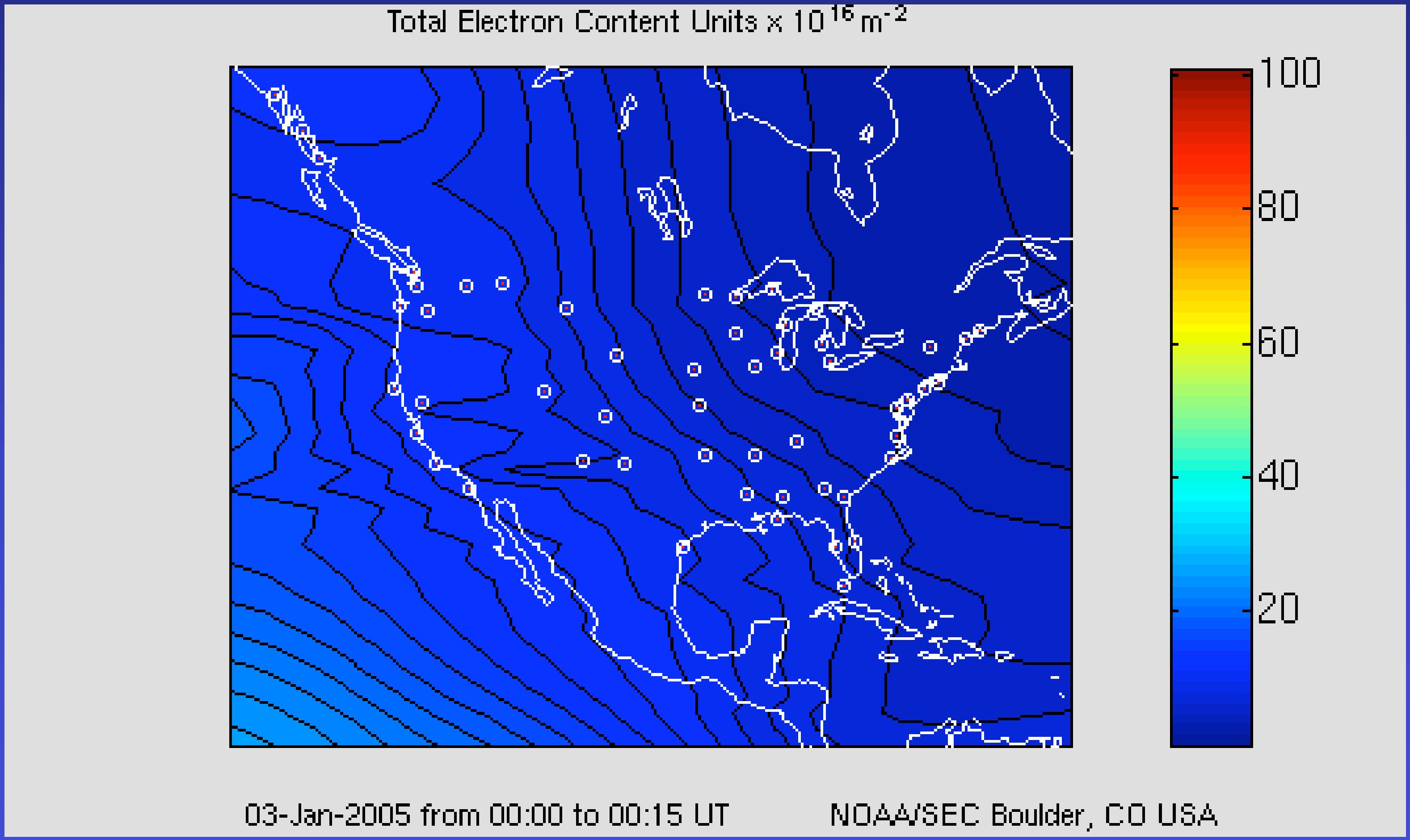
The Kalman Filter and extracting "information"





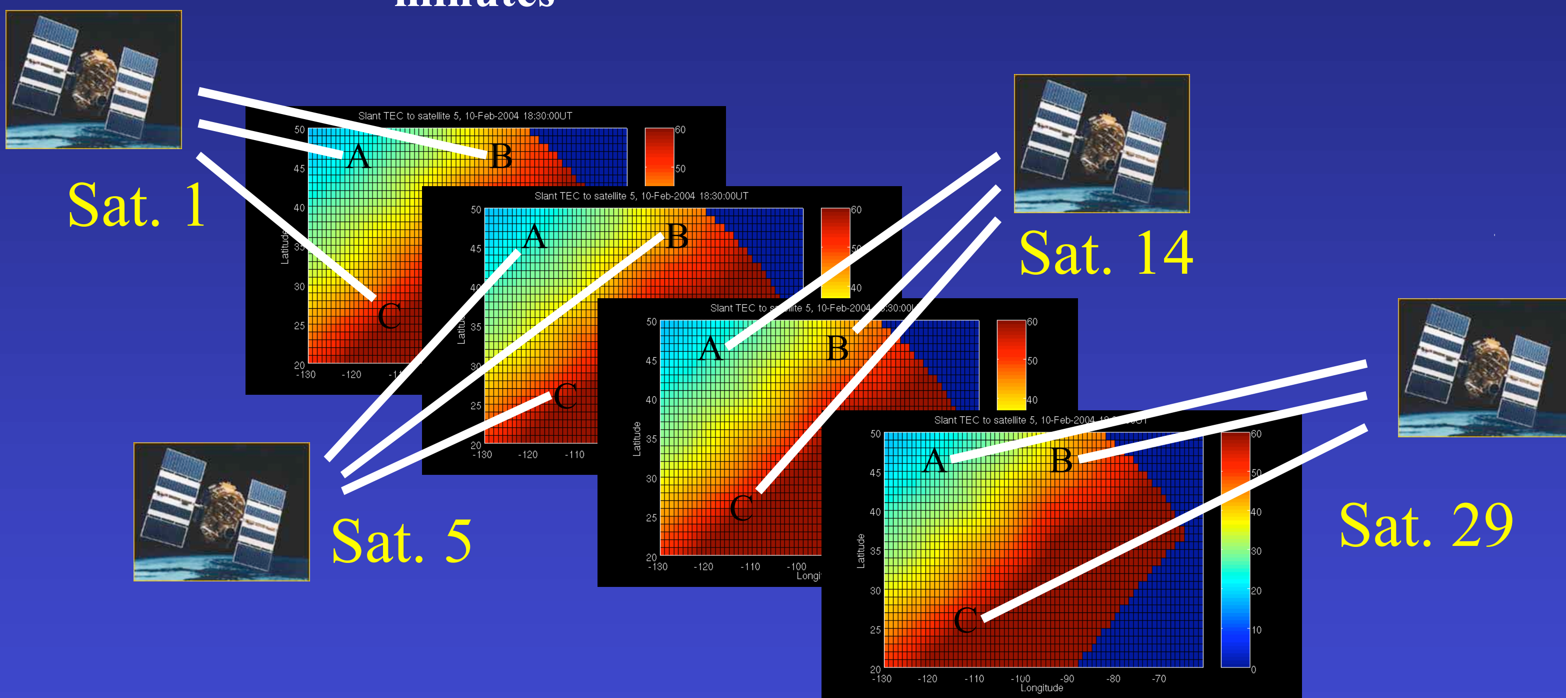
Primary Product: Vertical TEC

Real-time ionospheric maps of total electron content every 15 minutes



Slant-Path TEC Maps

2-D maps of of slant path TEC over the CONUS for each GPS satellite in view updated every 15 minutes



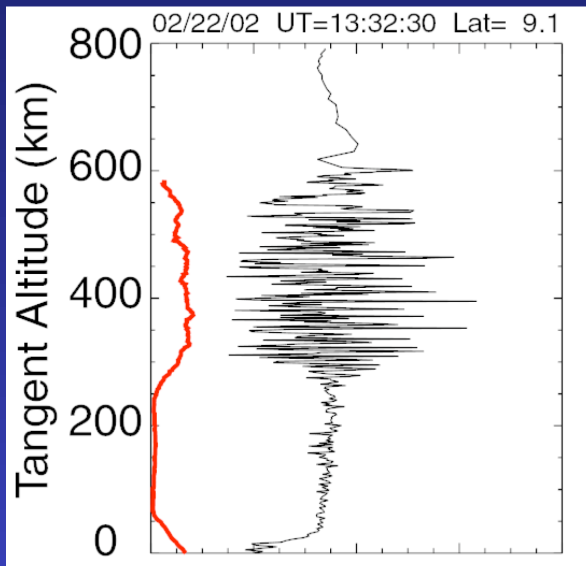
. . . . etc

Applications:

1. Ionospheric correction for single frequency GPS and NDGPS positioning
2. Dual-frequency integer ambiguity resolution for rapid centimeter accuracy positioning

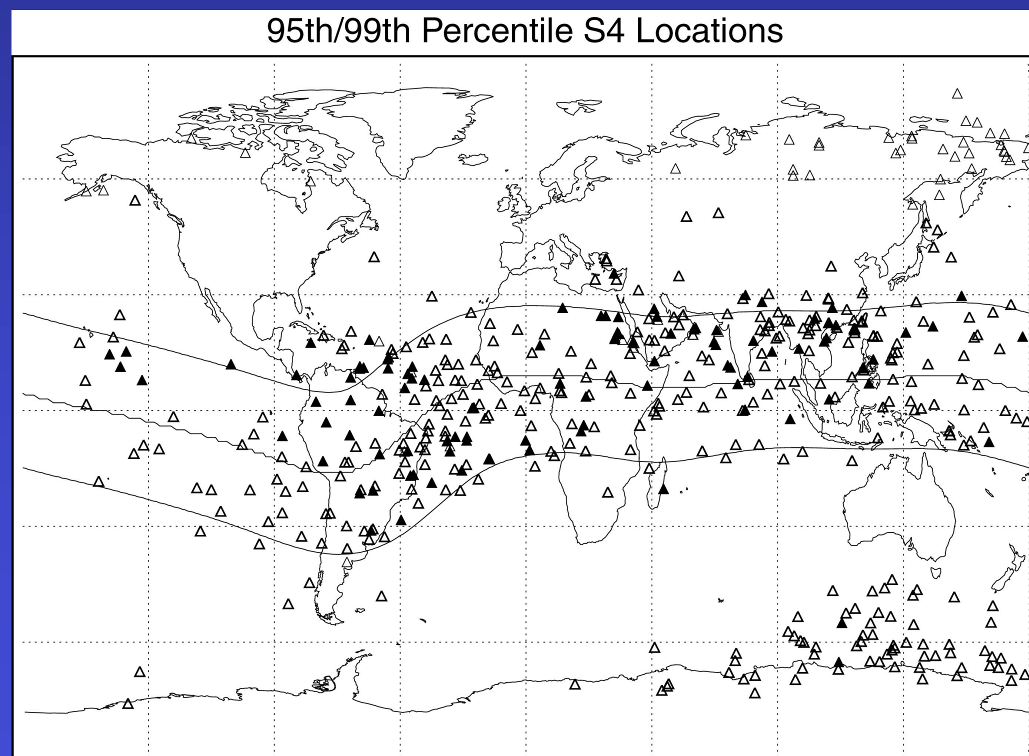
Scintillations

and Maps



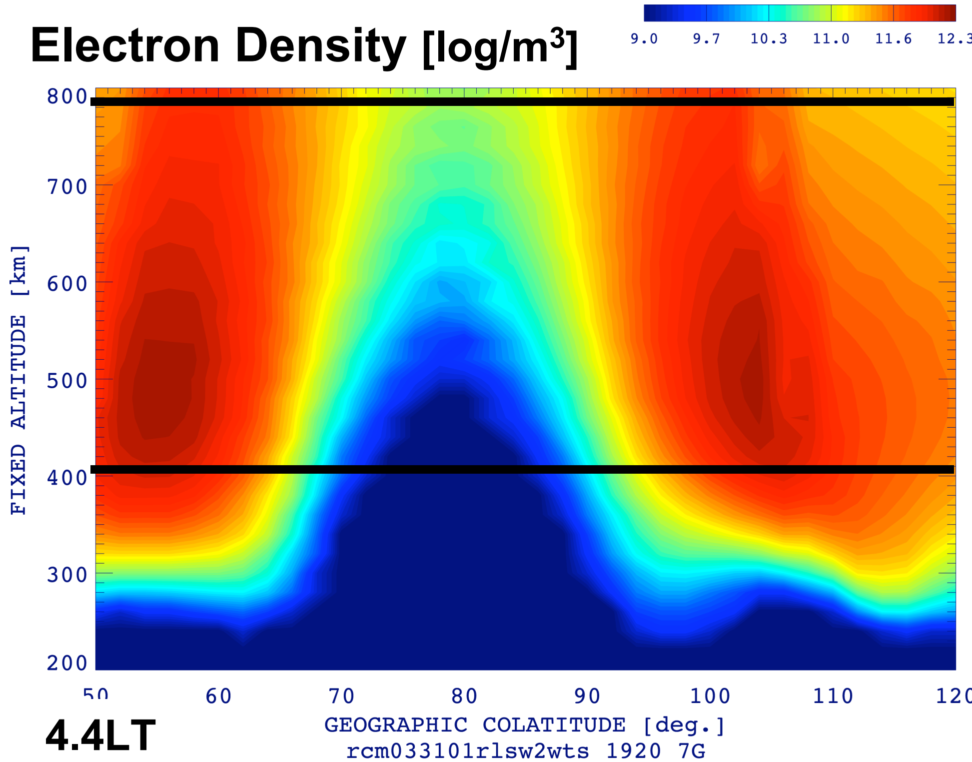
Signal-to-noise ratio

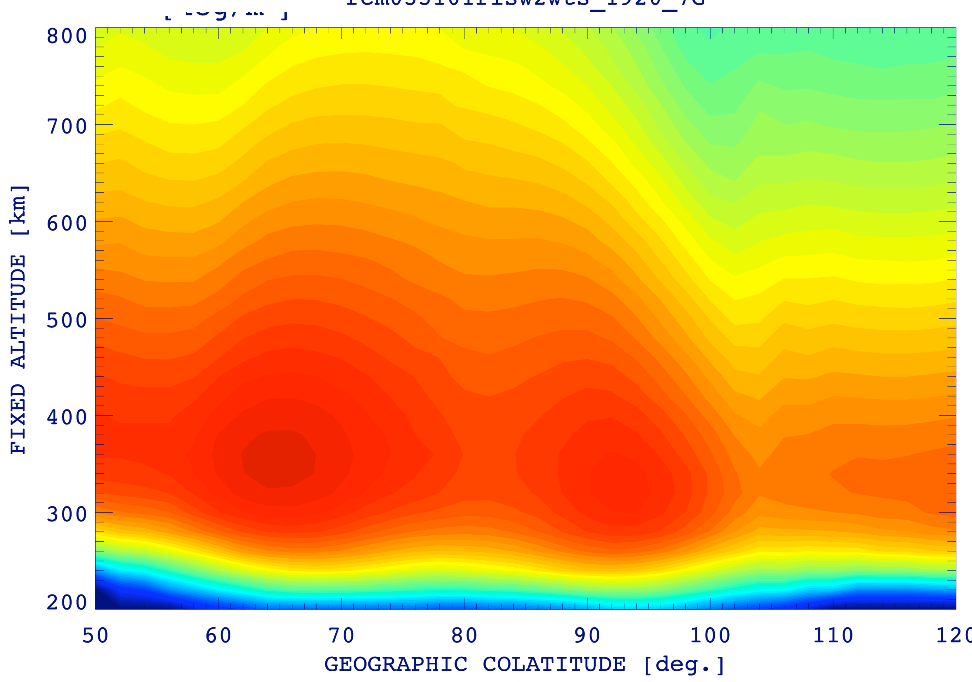
Distribution of high scintillation events



Courtesy:
Paul Straus
Aerospace Corporation

THE AEROSPACE CORPORATION

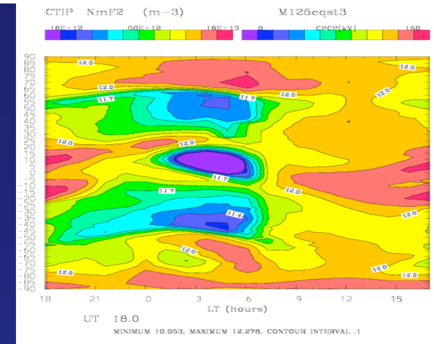


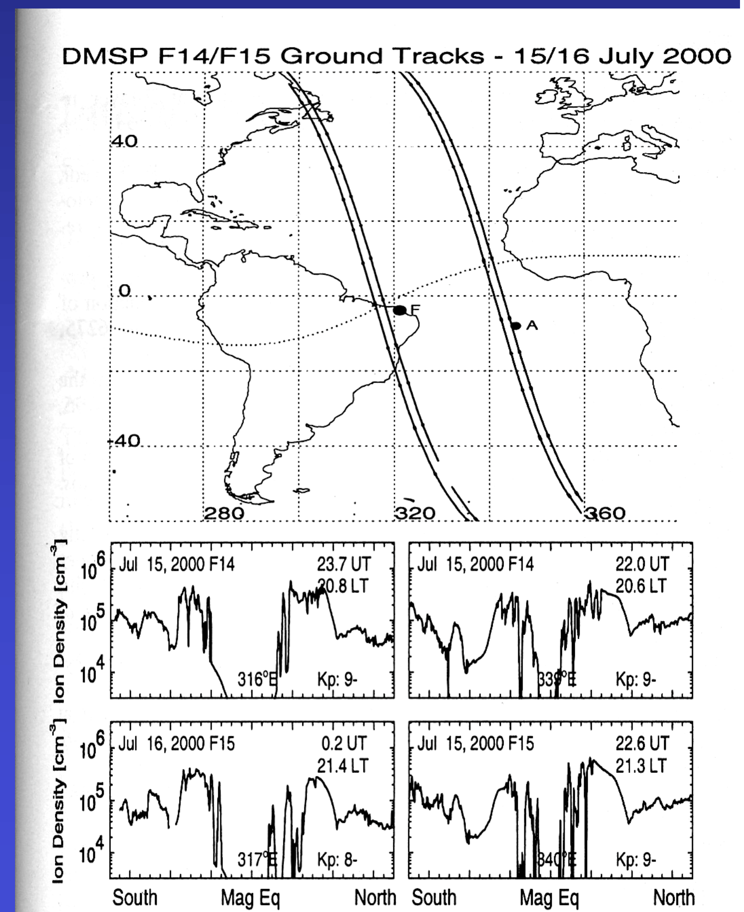


⇐ Storm

⇐ Quiet

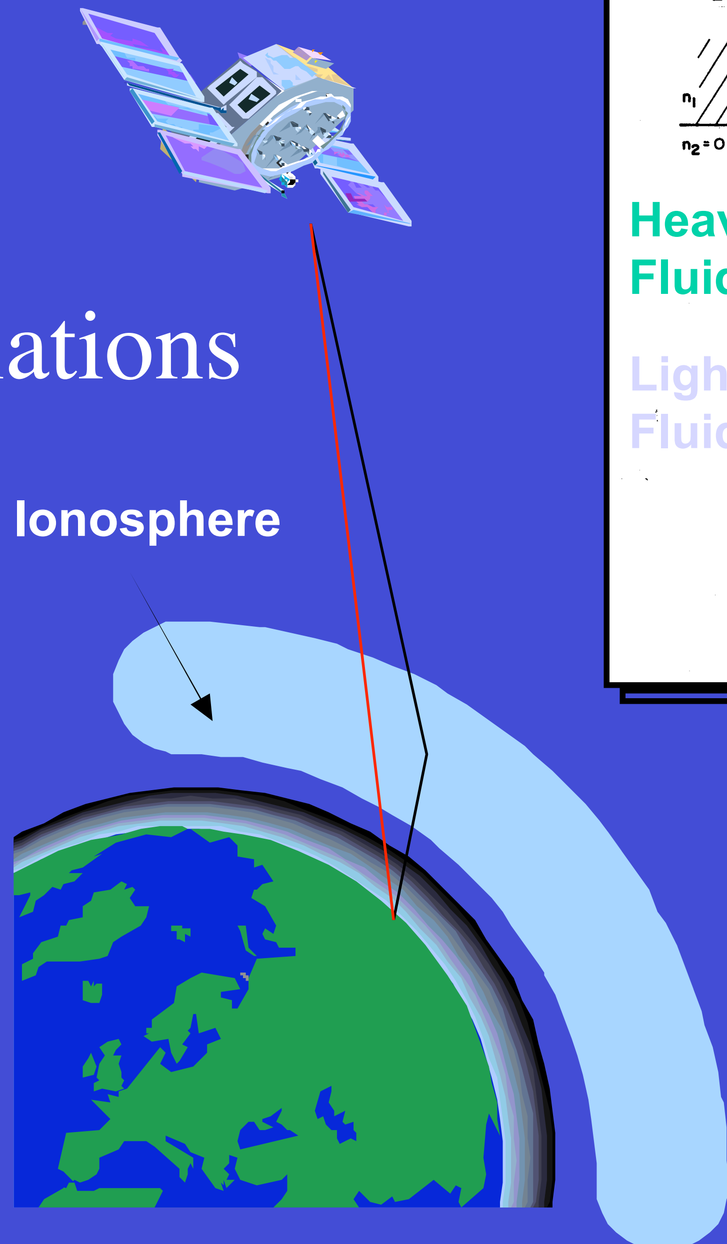
"Bite-outs"

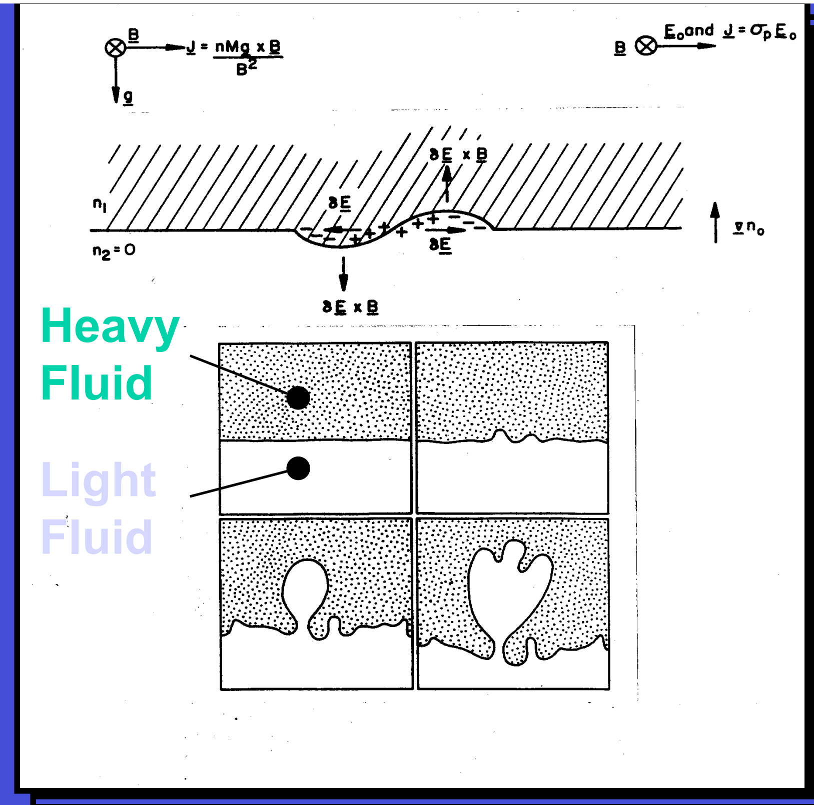




Basu et al. 2001

Scintillations

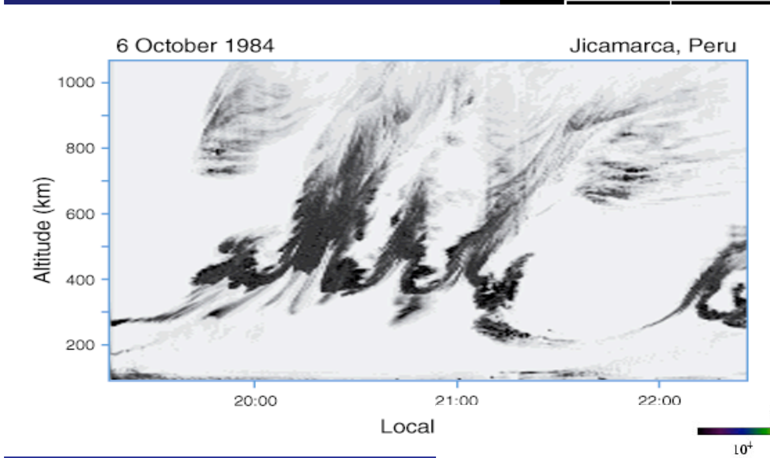


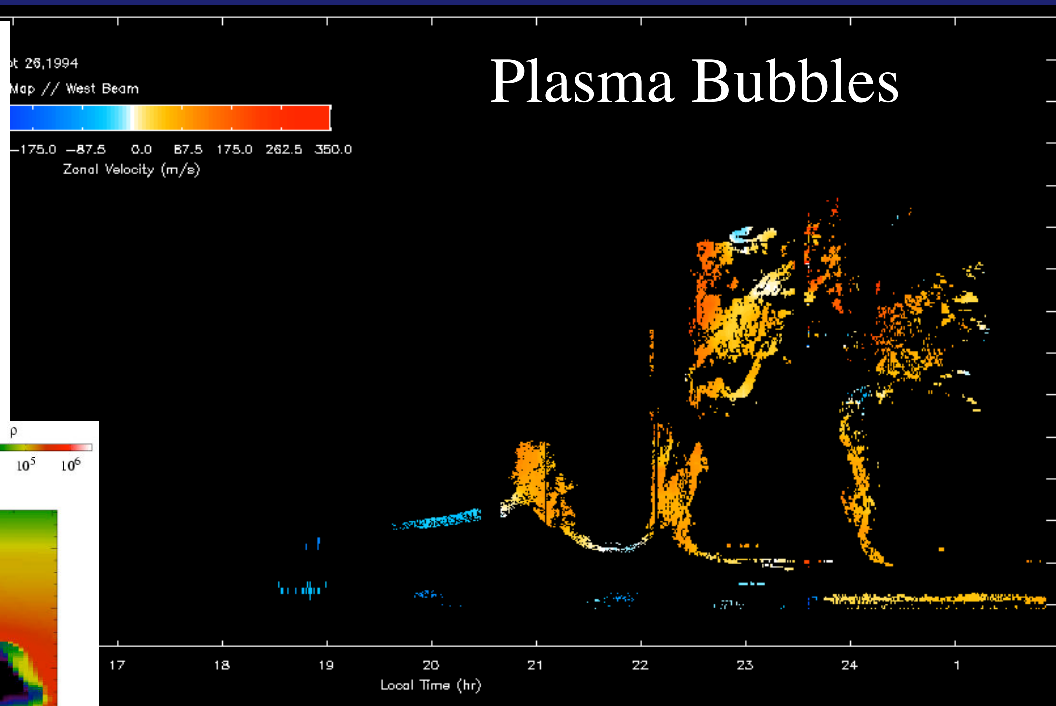


Steep bottomside density gradient during / after sunset

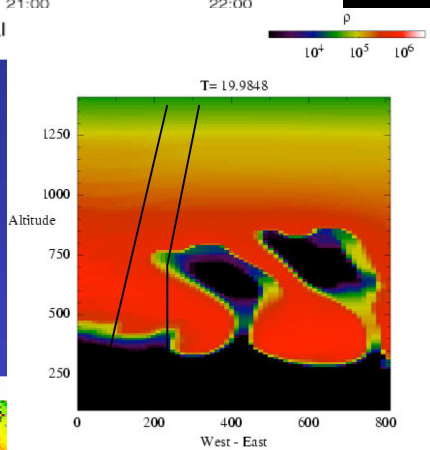
Fluid instability analog (Rayleigh-Taylor instability)

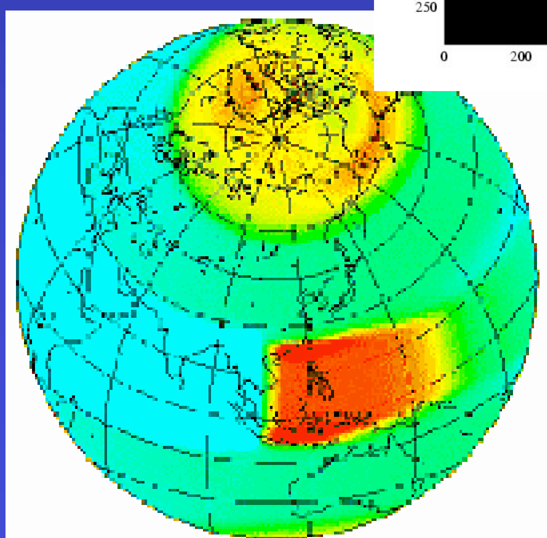
Plasma Bubbles



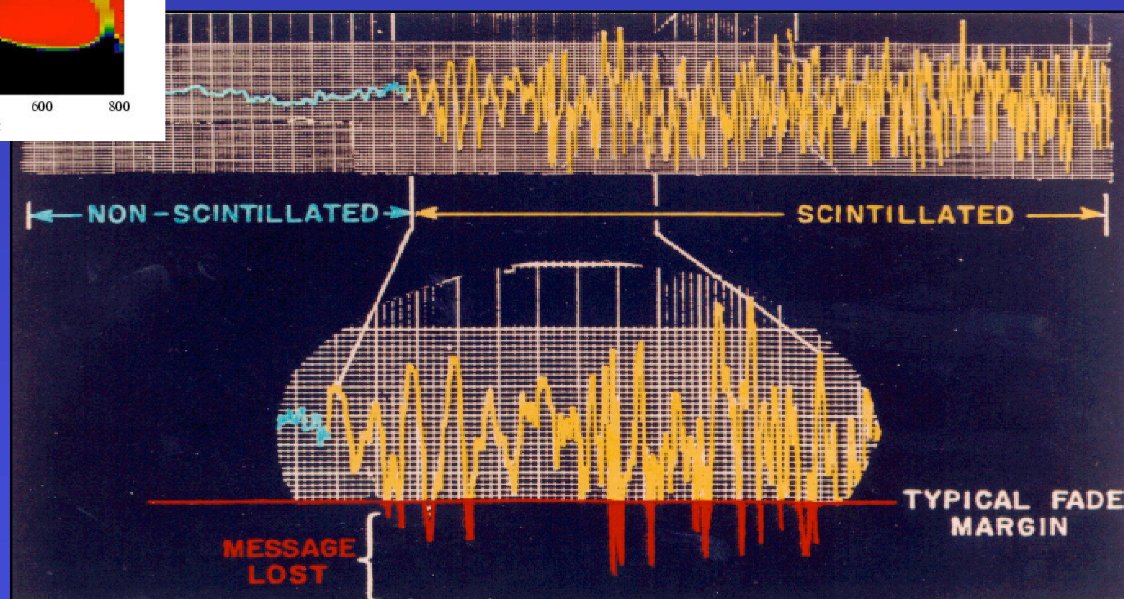


physical modeling



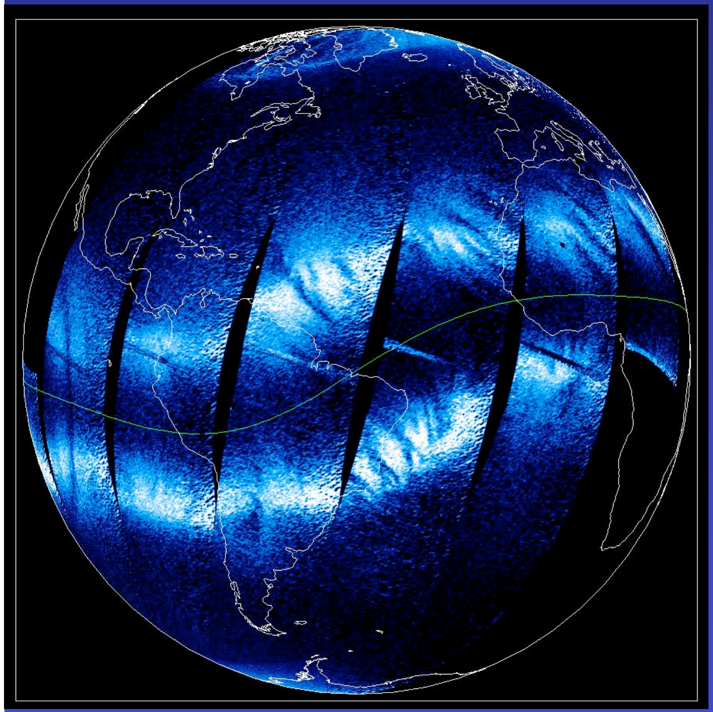


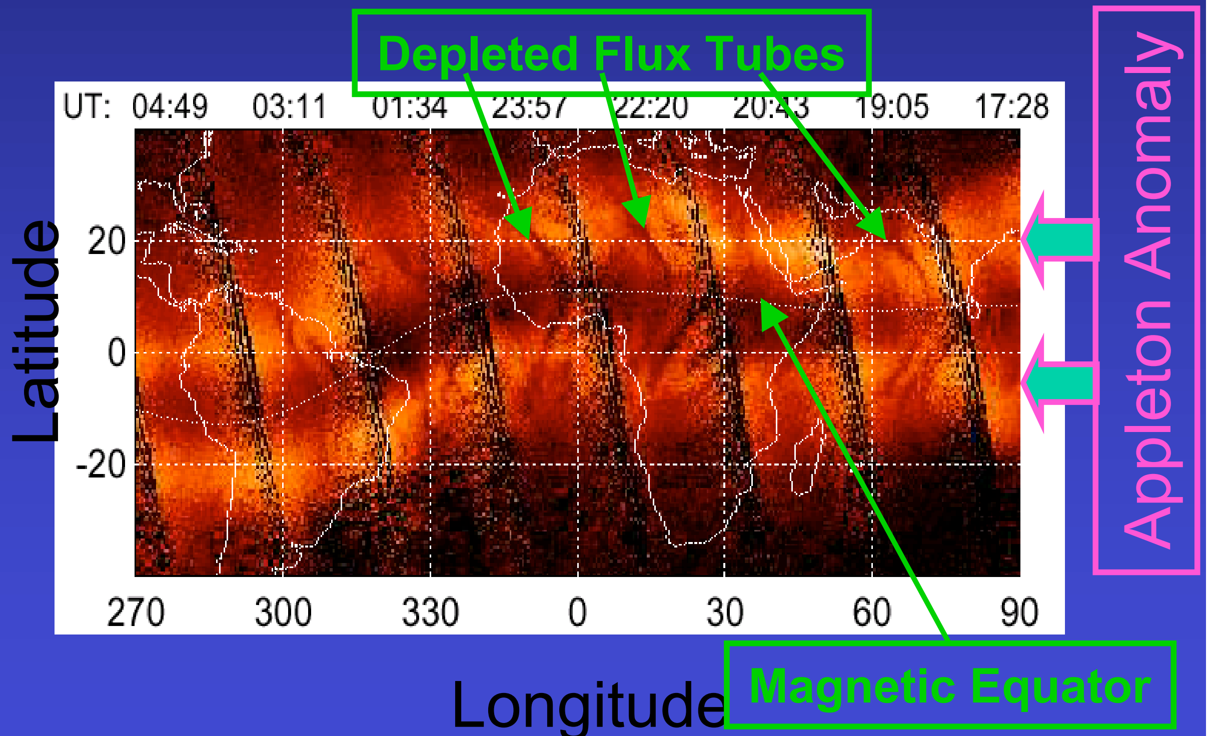
WBMOD: empirical model



GUVI Nighttime FUV Ionosphere Observations

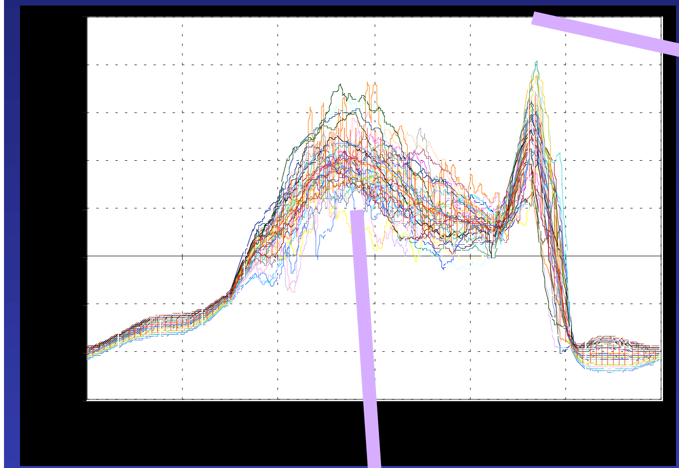
$e + O^+ \rightarrow O^*$ (135 nm) $\Longrightarrow$ $I = \alpha \int n_e^2\, ds$



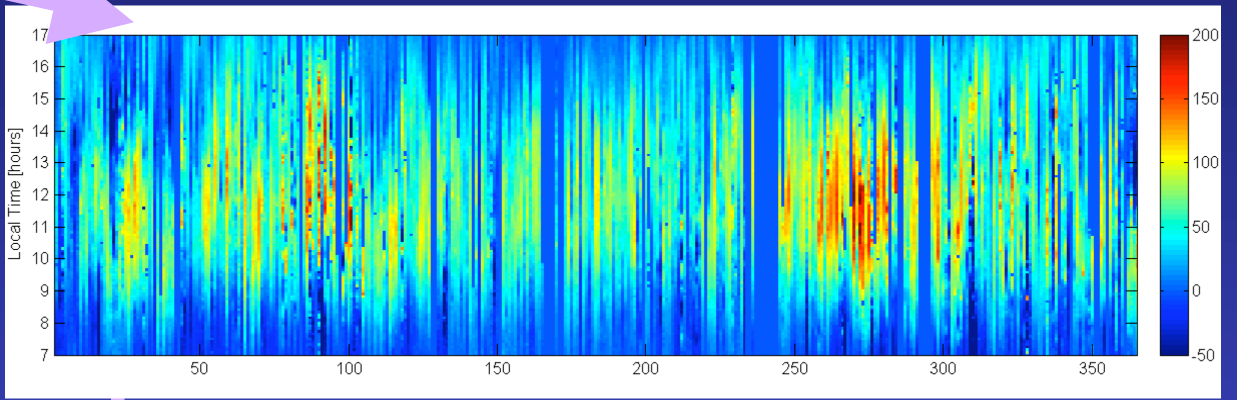


Courtesy APL

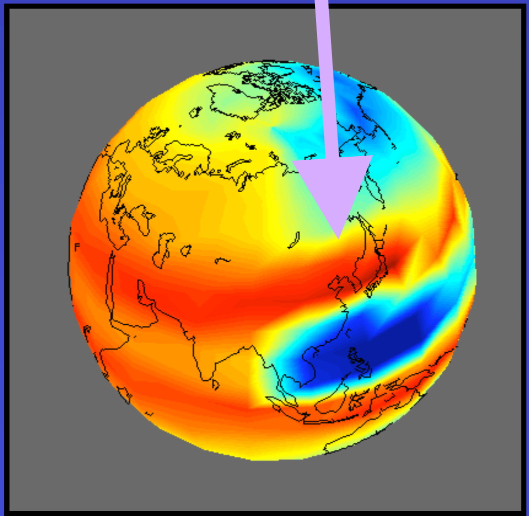
Motivation: Planetary wave periodicities in dayside ionosphere



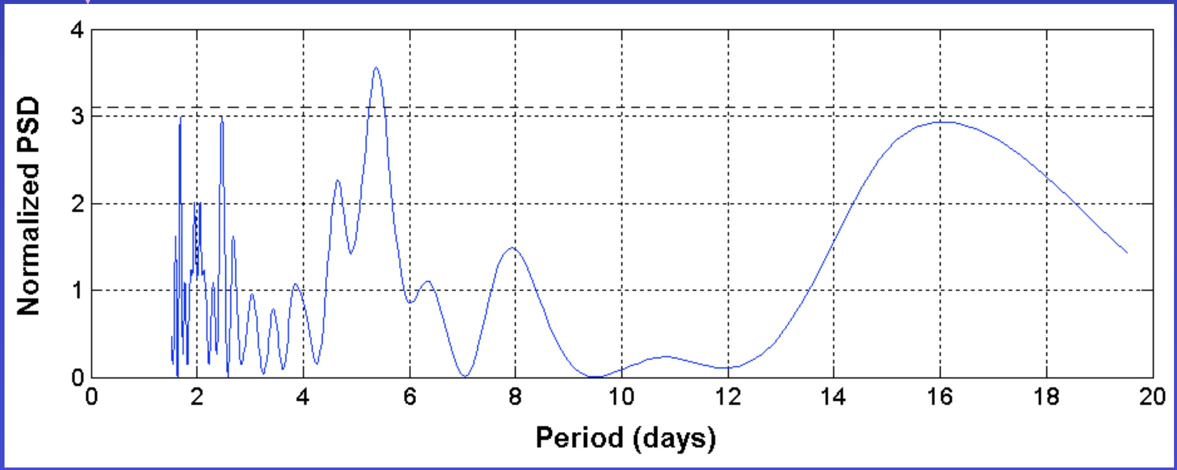
Dayside electrodynamics during 2001



Electrodynamics drives plasma transport

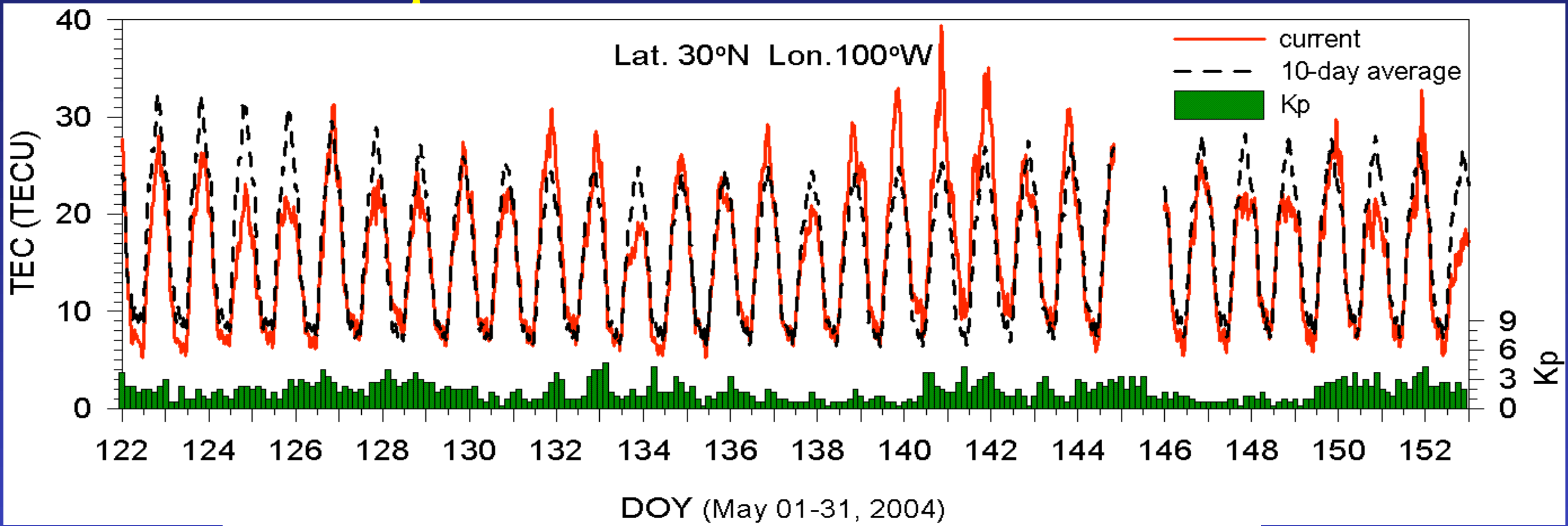


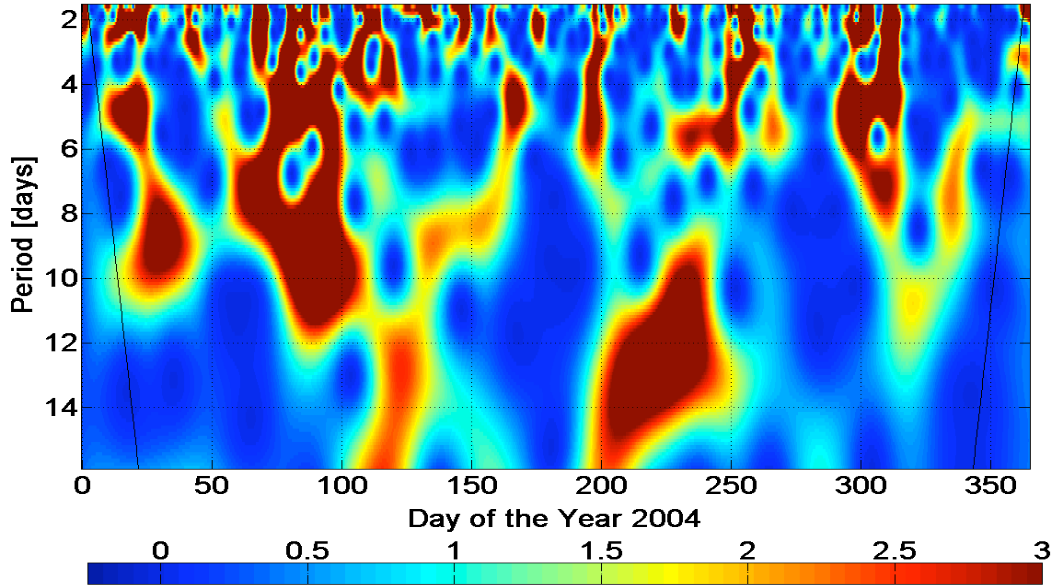
Possible PW signatures

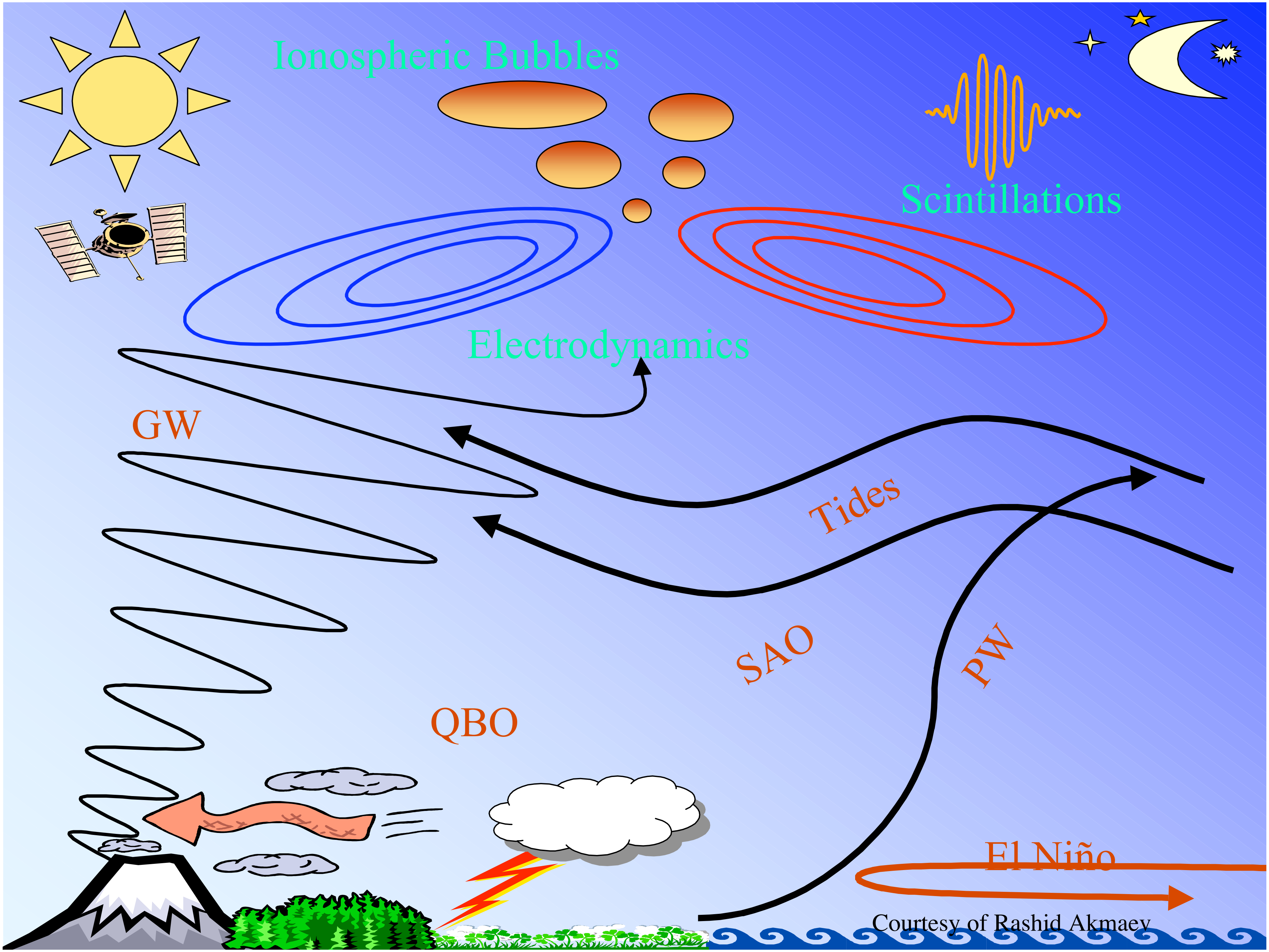


Courtesy D. Anderson & A. Anghel (2006)

Mid-latitude day-to-day variability in ionospheric total electron content






Ionospheric Bubbles
Scintillations
Electrodynamics
GW
Tides
SAO
PW
QBO
El Niño
Courtesy of Rashid Akmaev

Tidal signatures in nightside Equatorial Ionospheric Anomaly

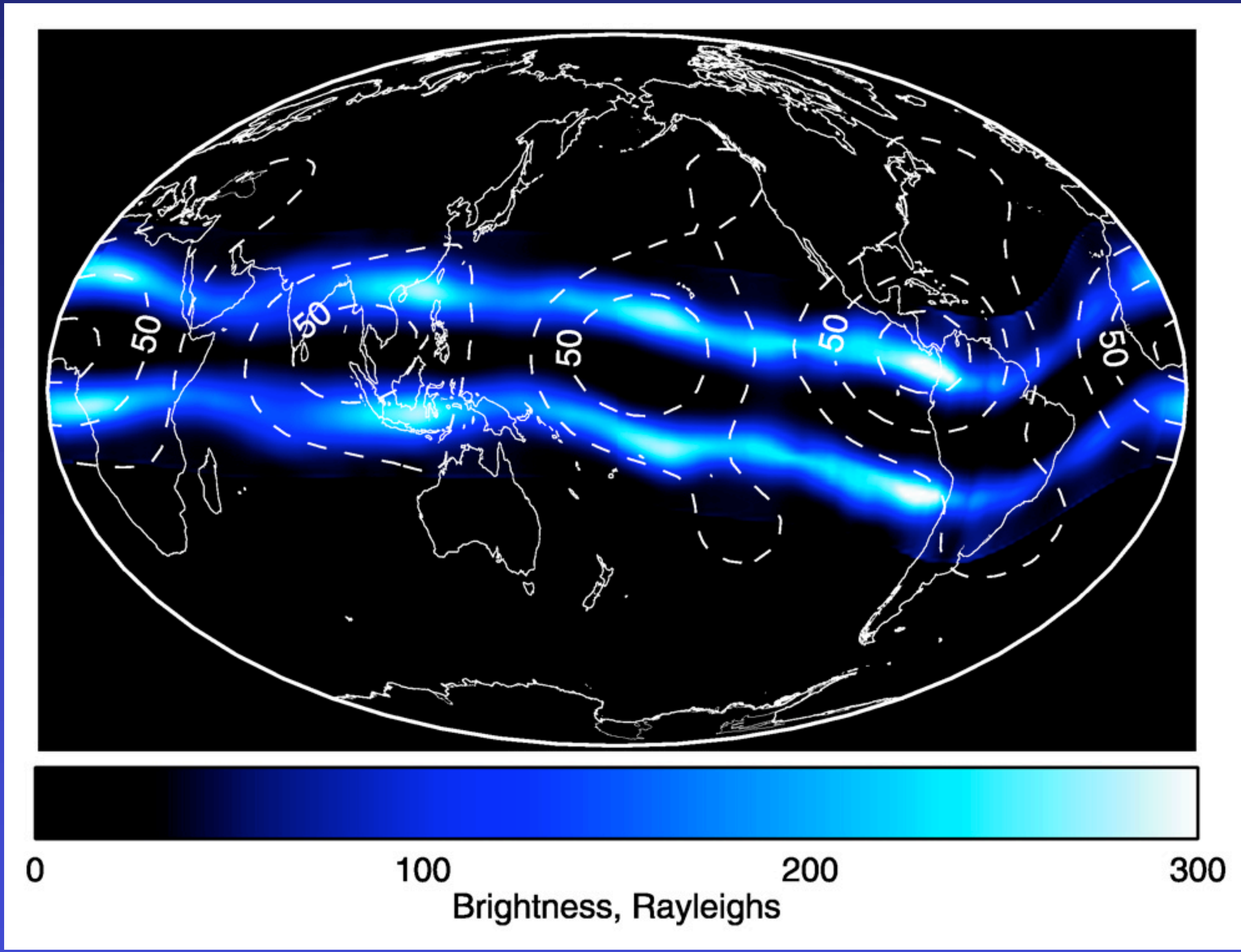


IMAGE composite of 135.6-nm O airglow (350-400 km) for March-April 2002 and magnitude of tidal temperature oscillations at 115 km (Immel et al., 2006).

Conclusion

- Many of the space weather effects on communication and navigation are a consequence of the response of the upper atmosphere to solar flares, coronal mass ejections, and solar proton events
- Day-to-day variability can also arise from the connections between terrestrial and space weather