Magnetosphere - Ionosphere coupling and its impact on our daily life!

Endawoke Yizengaw

Institute for Scientific Research, Boston College

What is the content of the lecture?

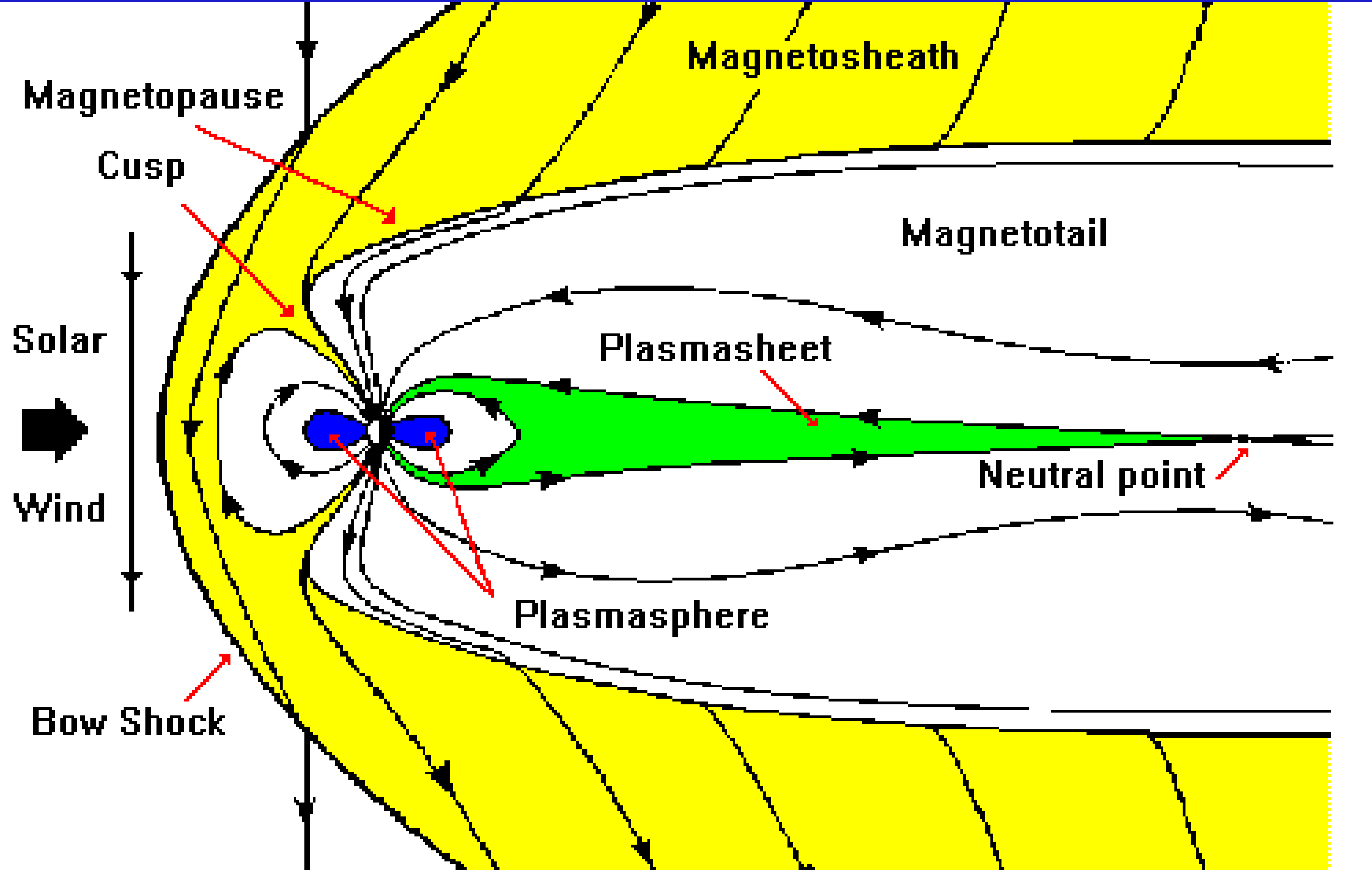
1st Part of the talk!

- What is magnetosphere?
- Why do we care about it?
- How does it communicate with the ionosphere?
- What happen during storm time, and what are the impacts on our daily life?
- How does ionosphere respond to magnetic storm?
- How do we monitor the stus of the ionosphere?
- Some prominent MI coupling phenomenon?

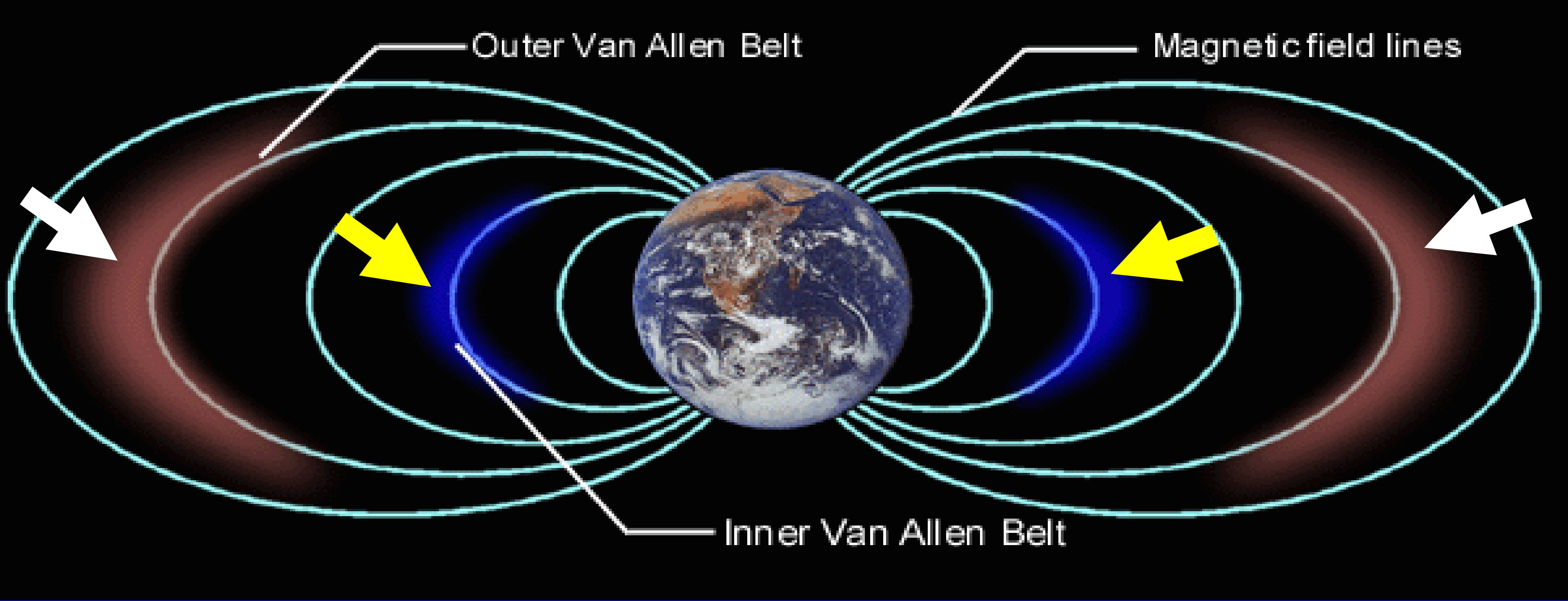
2nd Part of the talk!

- Will introduce AMBER magnetometer and SCINDA GPS networks

Where is the Magnetosphere?



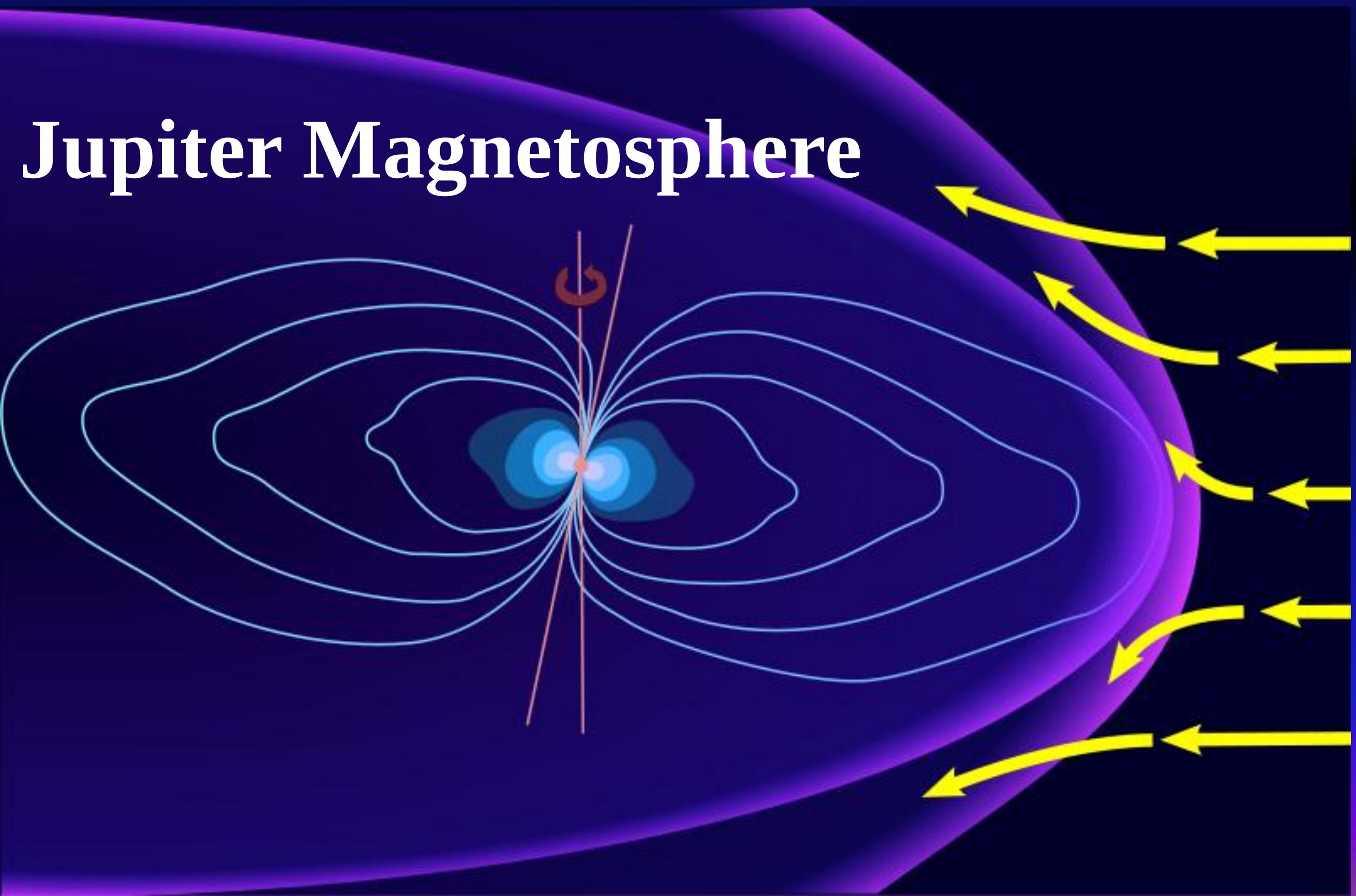
What does the magnetosphere contains mainly?



- **Protons with 10-100 MeV at 1.5 R_E, attributed to albedo neutron decay and cosmic radiation interaction with the upper atmosphere.**
- **population of trapped ions and electrons with the energy of ~1MeV at 2.5–8 R_E.** **(1e produce ~ 1.6 x 10E-11 J)**

Are we alone or is there any other planets that have magnetosphere?

Mercury, Earth, Jupiter (Ganymede), Saturn, Uranus, and Neptune have magnetic fields



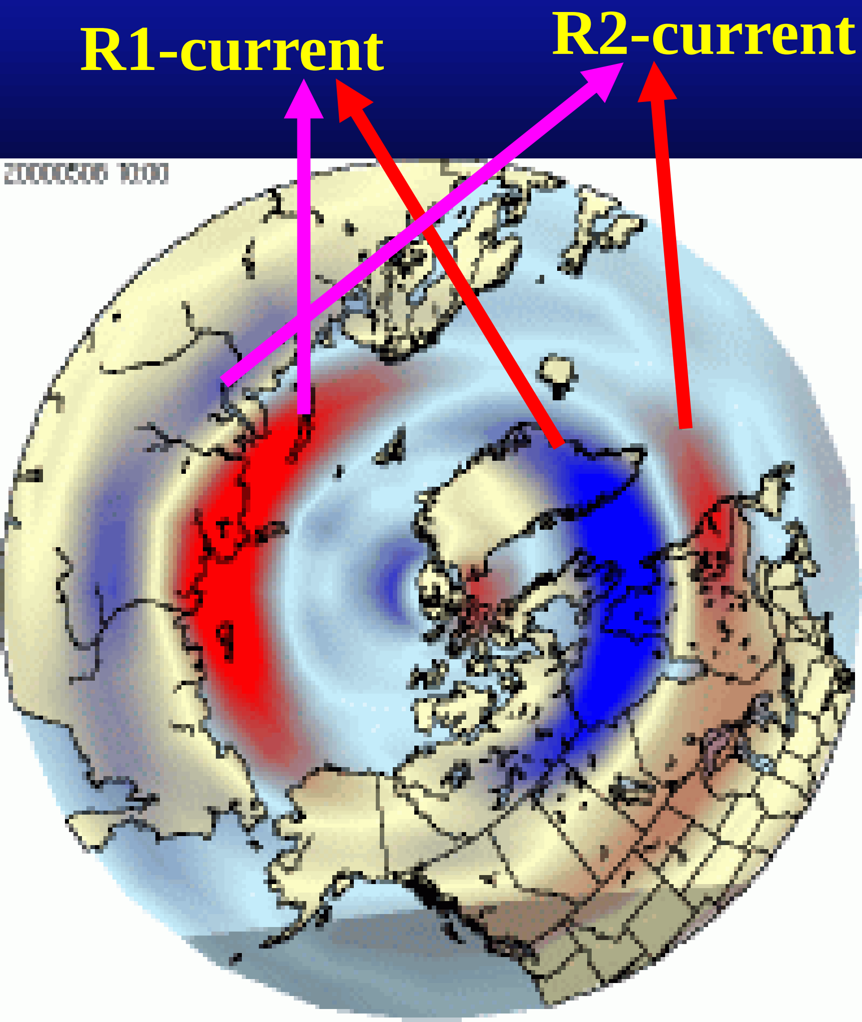
- Wider and flatter
- The biggest magnetosphere in the solar system
- MPP ~ 50 -100R_J
- MTL ~ 7000R_J
- R_J ~ 71,500km

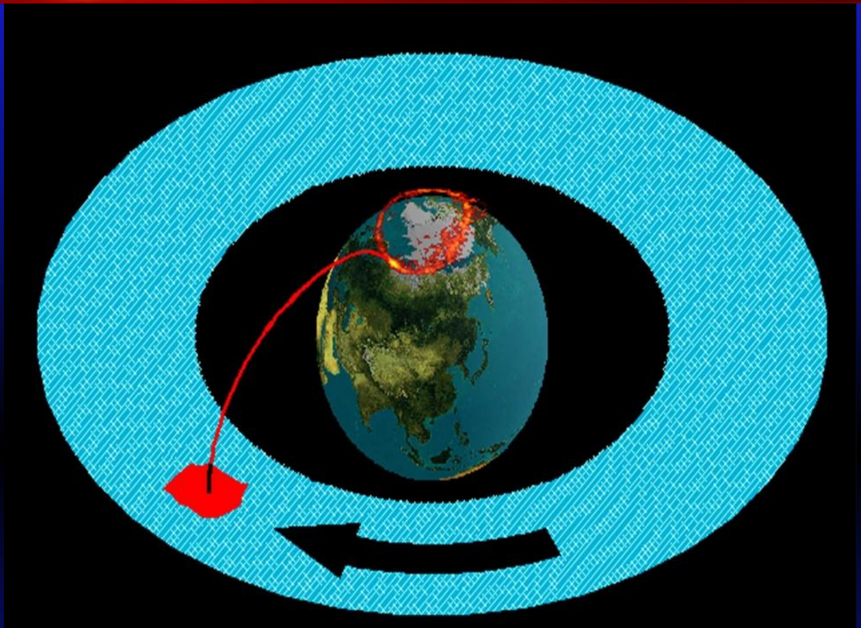
But why do we care about the magnetic fields? What role do the magnetic fields play in Space Weather?

- Organize the motion of charged particles
- It leads the Solar wind particles out into Interplanetary space (IMF)
- It protects us from solar wind and cosmic rays (Earth's magnetosphere)
- Magnetic field of Earth can accelerate particles to high energies

How does magnetosphere and ionosphere communicate?

Through Current





What are ionospheric current?

- Connect the magnetosphere to the ionosphere
- Can flow along the magnetic field (FAC)
- Can perturb power grids

How does that affect the ionosphere?

- Ionization levels change (source and loss)
- Transport of ionization from one altitude to another and from one latitude to another
- Changing solar illumination (day, season, solar activity)

This ionospheric dynamics gets worst during magnetic storm time

So what? Why do we care about ionospheric dynamics?

Electronic Communication

How does the ionospheric dynamics in particular and space weather in general impact it?

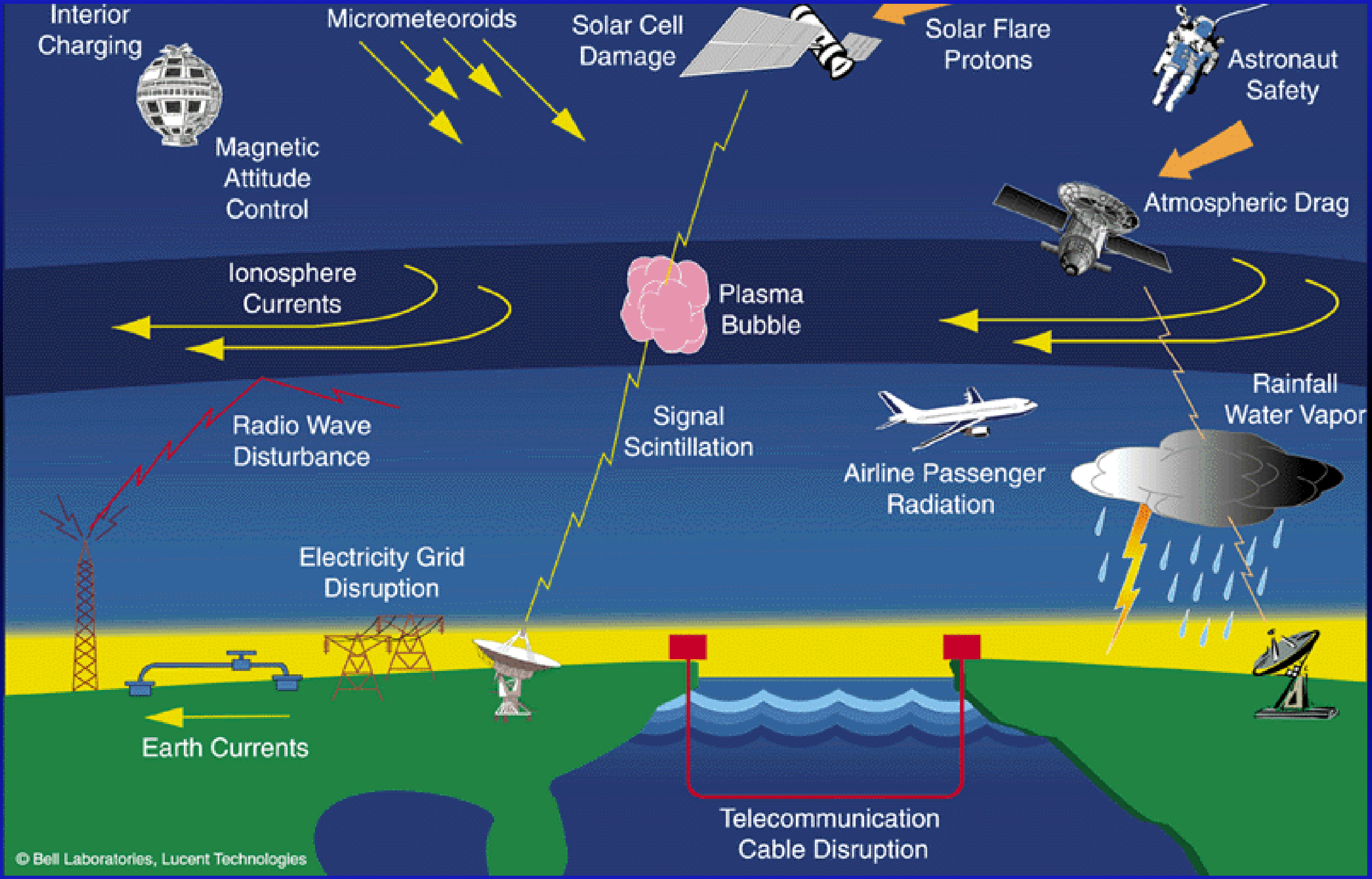
Well! How do you get information or how do we communicate with the rest of the world?

Radio wave!

How does the ionosphere interacts with Radio Waves?

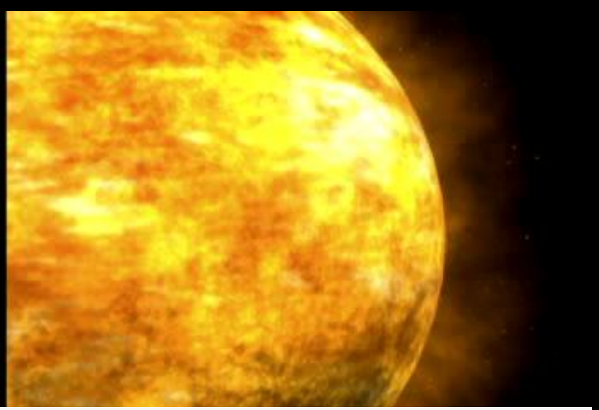
- **Can refract it:**
  - Slows down waves and leads to dispersion
- **Can reflect it:**
  - Allows us to have OTH radio communication
- **Can Scatter it:**
  - Causes signal degradation and loss
- **Can Absorb it:**
  - Causes HF radio blackout

How Wide variety of technologies are depend on space weather impacts



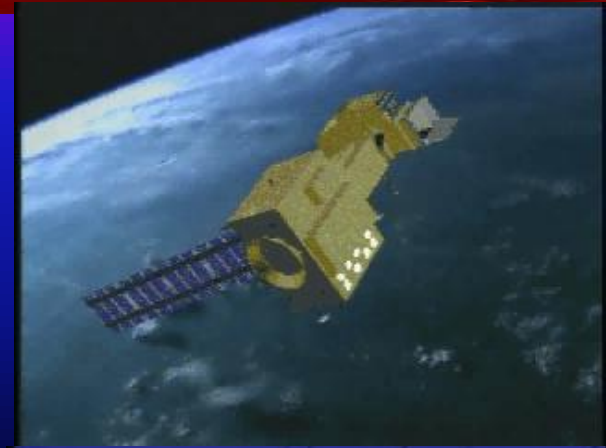
All these instruments are in trouble during magnetic storm time

What happens during a geomagnetic storms?



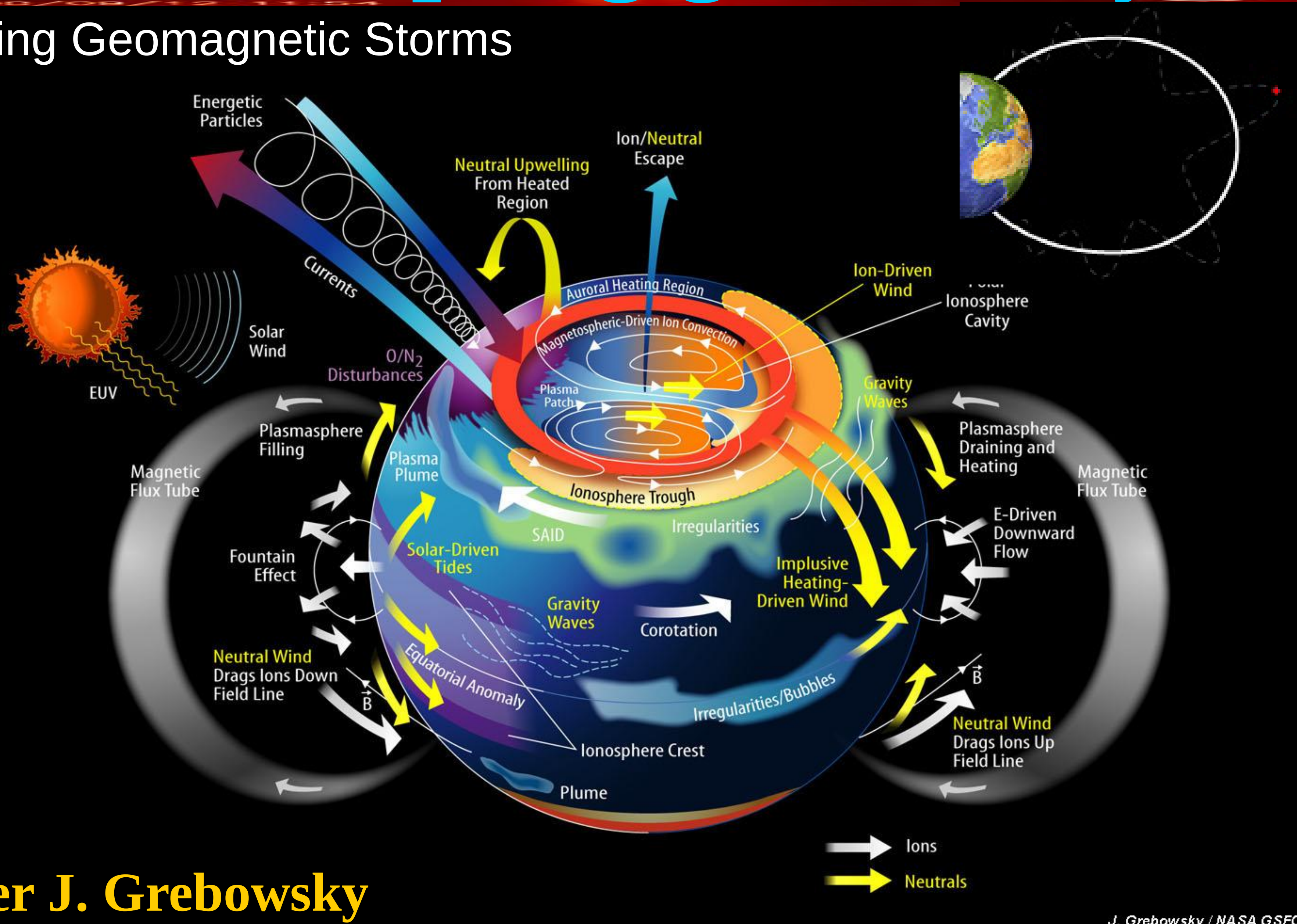
- CME or shock compresses the magnetosphere
- Ring Current and Radiation Belts intensify
- Ionospheric Currents intensify
- Auroral oval expands equatorward and poleward

Possible consequences



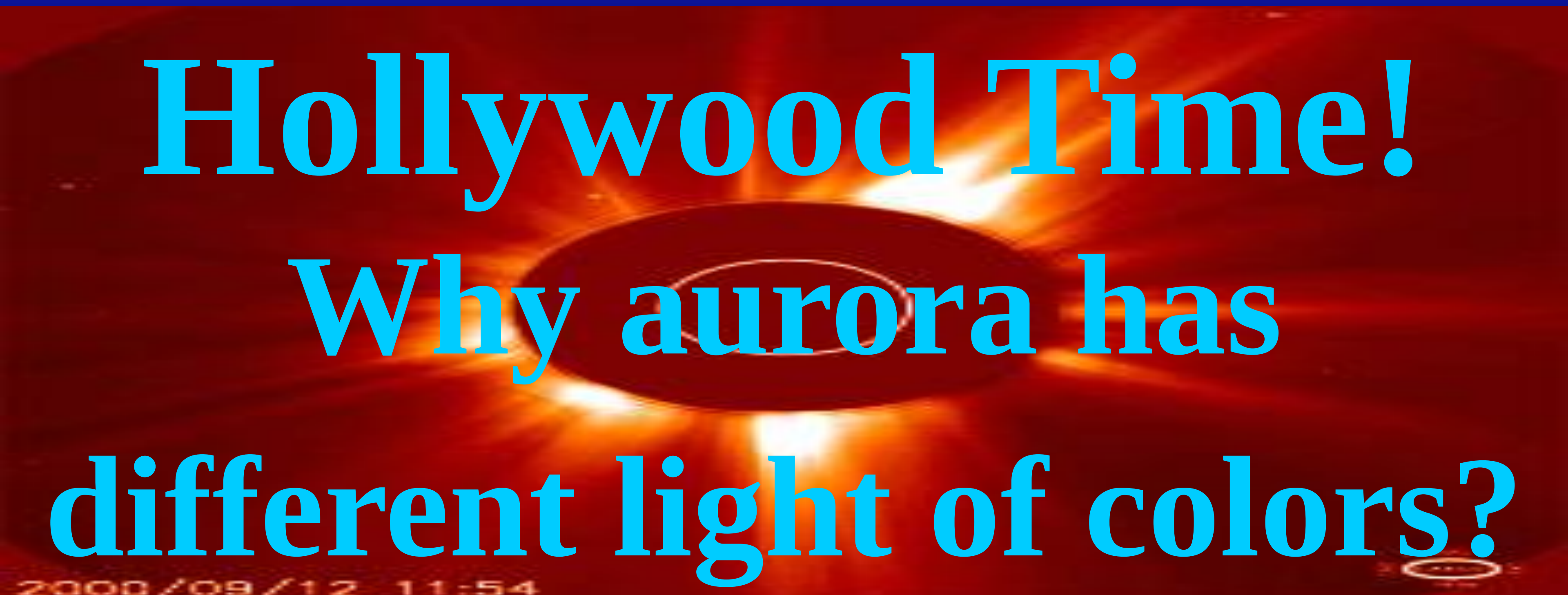
M-I coupling gets messy

During Geomagnetic Storms



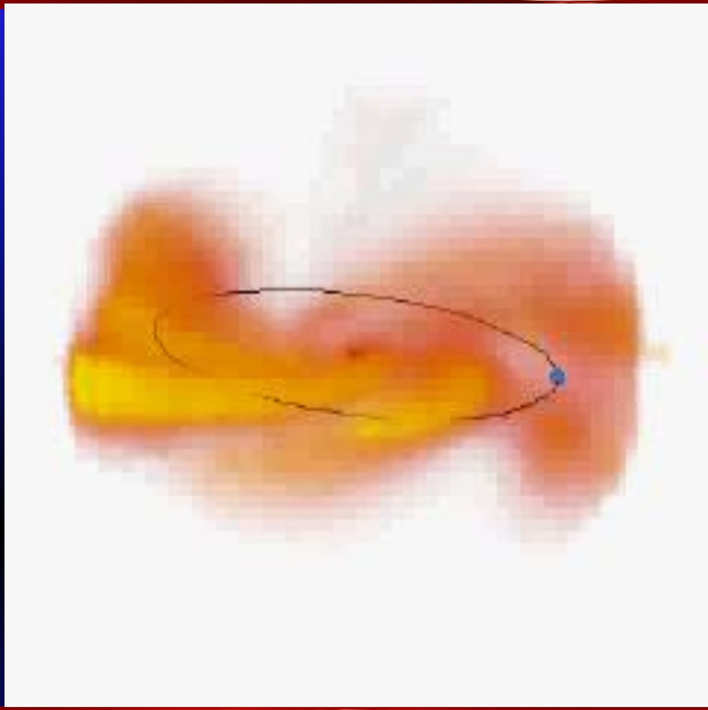
After J. Grebowsky

Hollywood Time!
Why aurora has different light of colors?



What Causes Storms?

- CME
- Shocks
- High Speed Streams (CIR storms)
- Flares are important for impulsive events, but are not the cause of most major storms

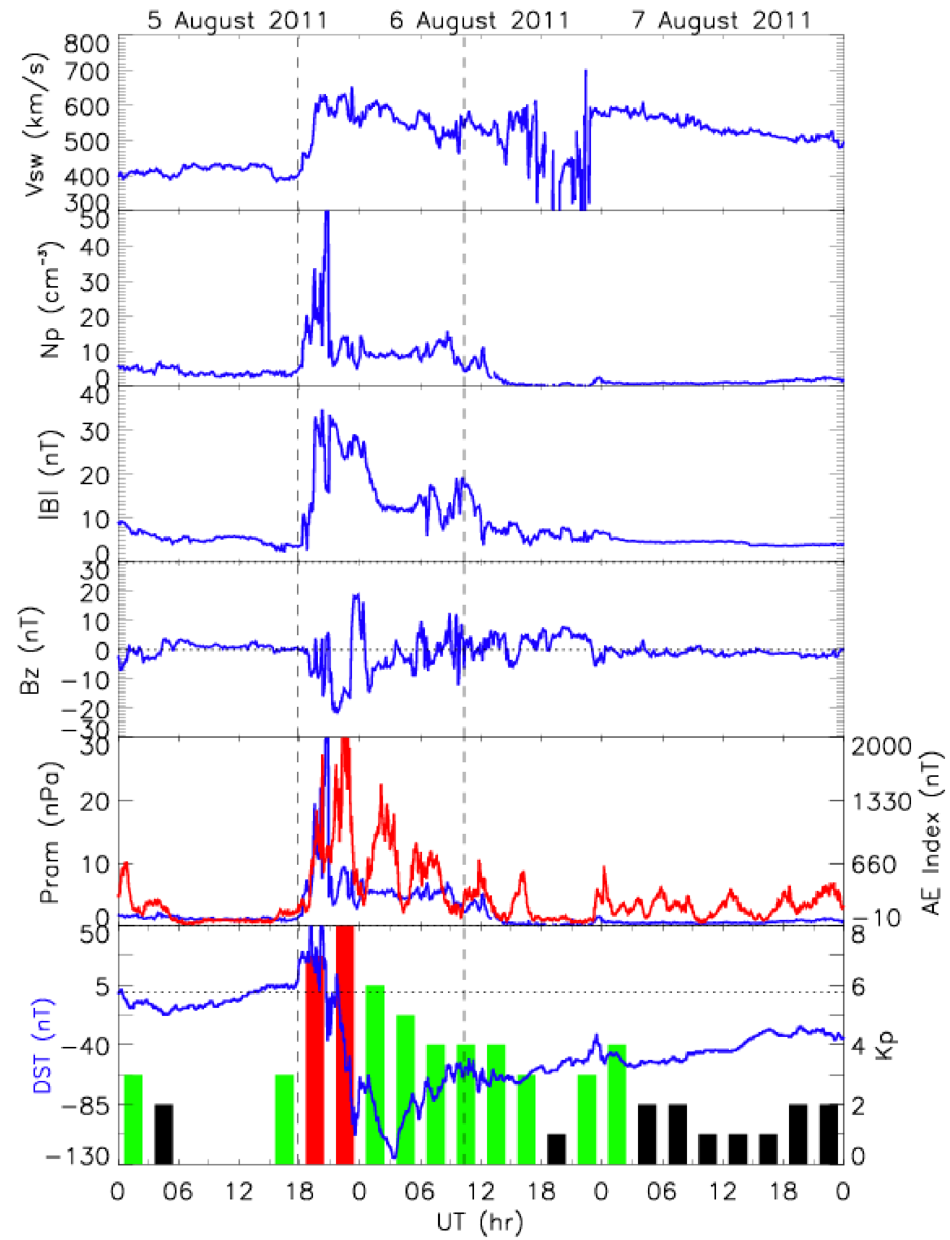


How do we know this?

- Ground observations of aurora and magnetic field
- Satellite observations of radiation, plasma, and electric and magnetic fields

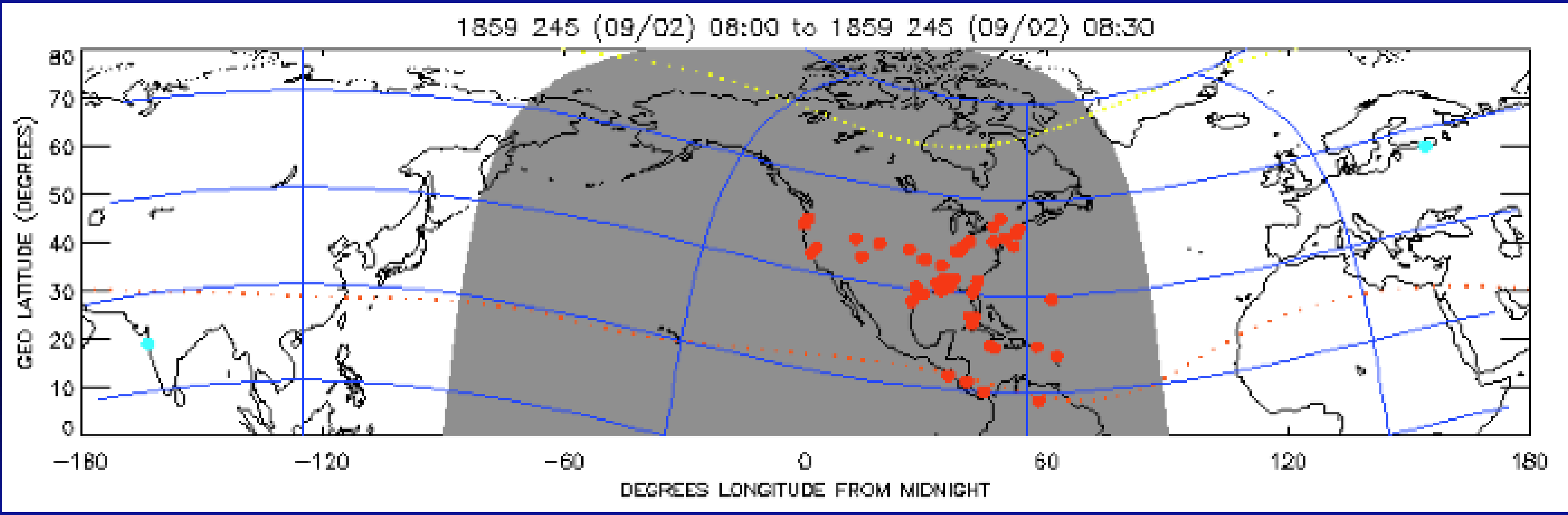
How do we measure a storm?

- Indices (Richter Scale - earthquakes, Saffir-Simpson-hurricanes) - Kp, Dst for storms
- **Kp** - planetary magnetic field disturbance index (logarithmic from 0 to 9)
- **Dst** - disturbed stormtime index - also a magnetic index that examines the strength of the ring current.



What was the biggest storm ever recorded?

September 2, 1859 Event



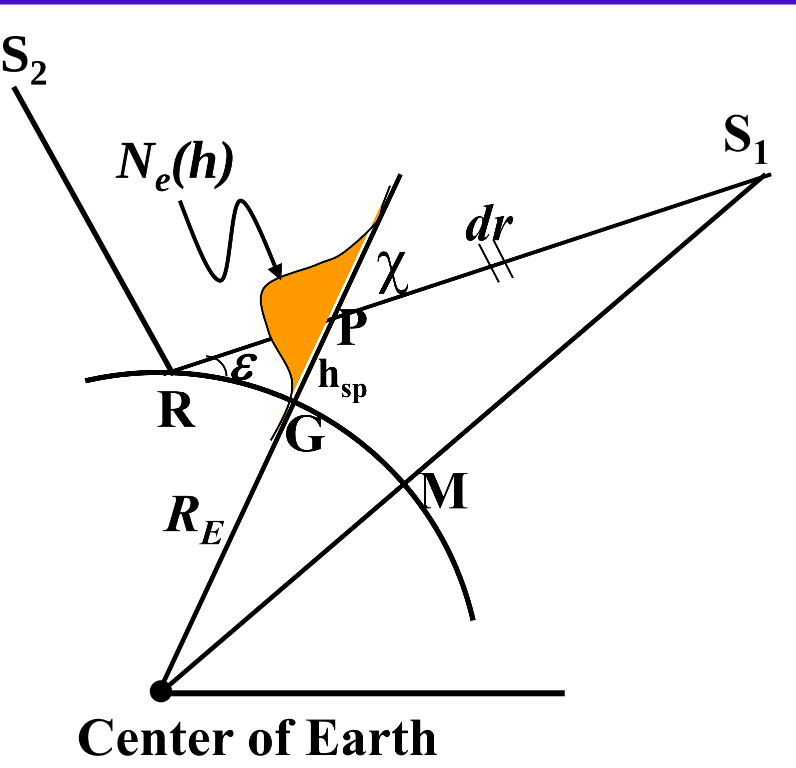
New York Times – "… it was chiefly confined to the southern heavens [south of NY], and hence was more properly an Aurora Australis than an Aurora Borealis"

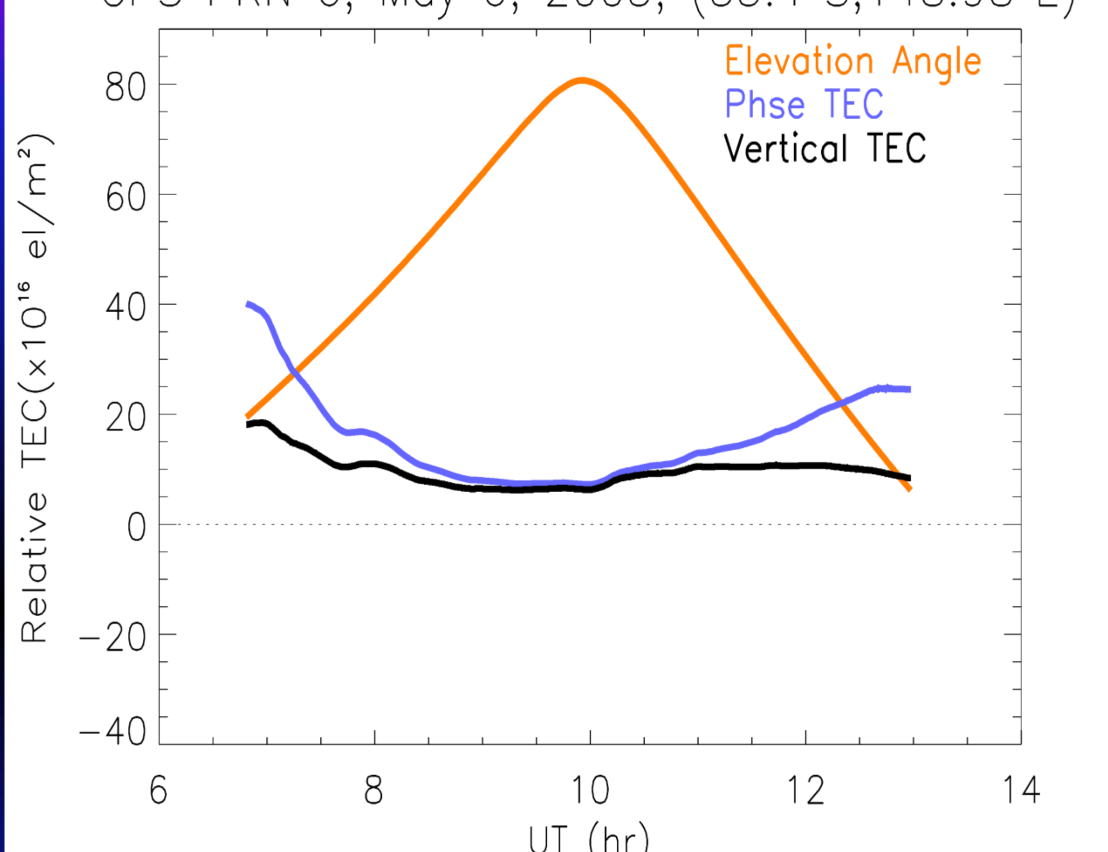
How does the ionosphere respond to such big magnetic storm?

How do we monitor the ionosphere?

GPS/GNNS, TOPEX/JASON, and other LEO satellites

What exactly can we measure with GPS?





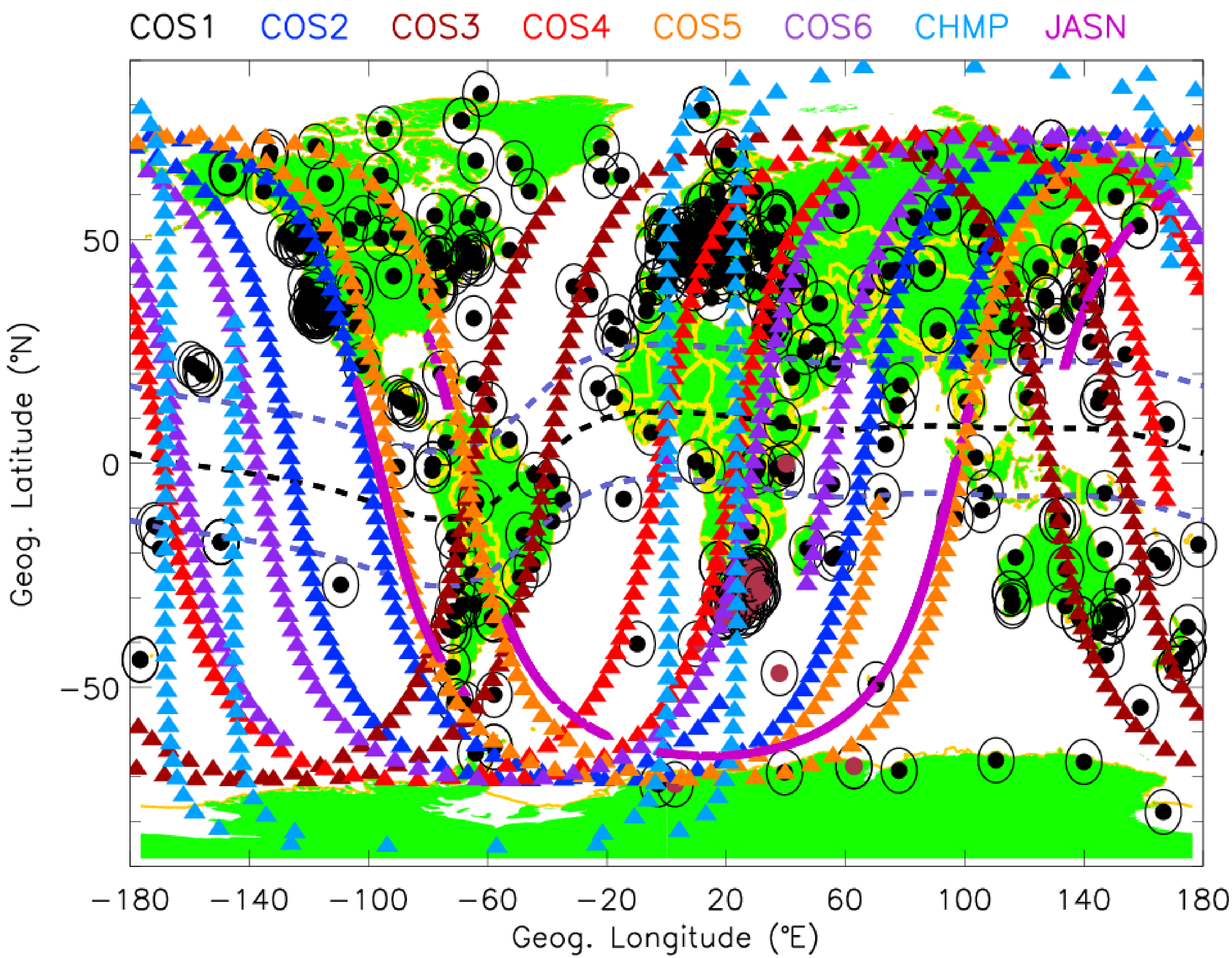
$$VTEC = \cos\chi \int_R^T N_e \, dl$$

$$1TECU = 1\times 10^{16} \, el/m^2$$

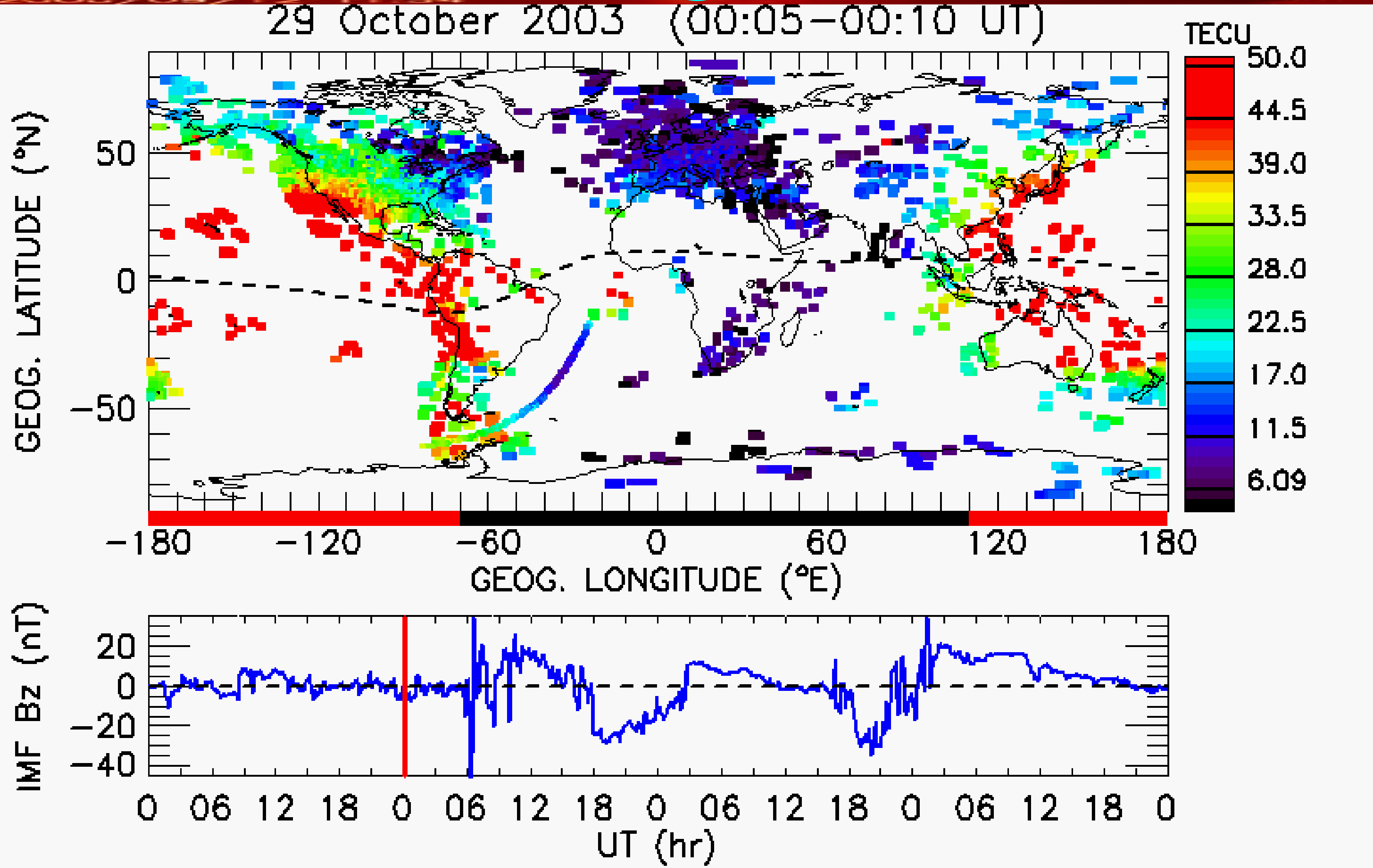
$$STEC_C = \int_R^S N dr = 9.509\,(P_2 - P_1)$$

$$STEC_p = \int_R^S N dr = 9.509\,(L_2 - L_1)$$

Global GPS receivers network



Ionosphere is boiling like a water at 100 degree cc



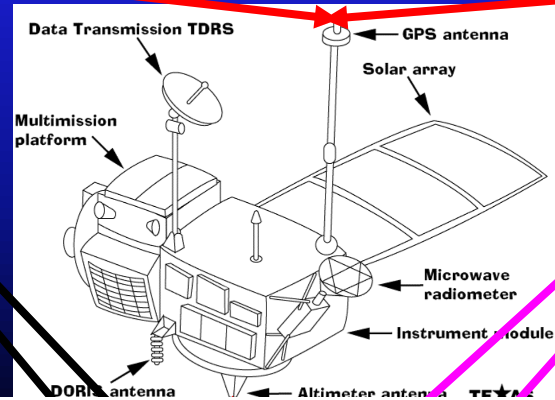
TOPEX/JASON Altimeter TEC

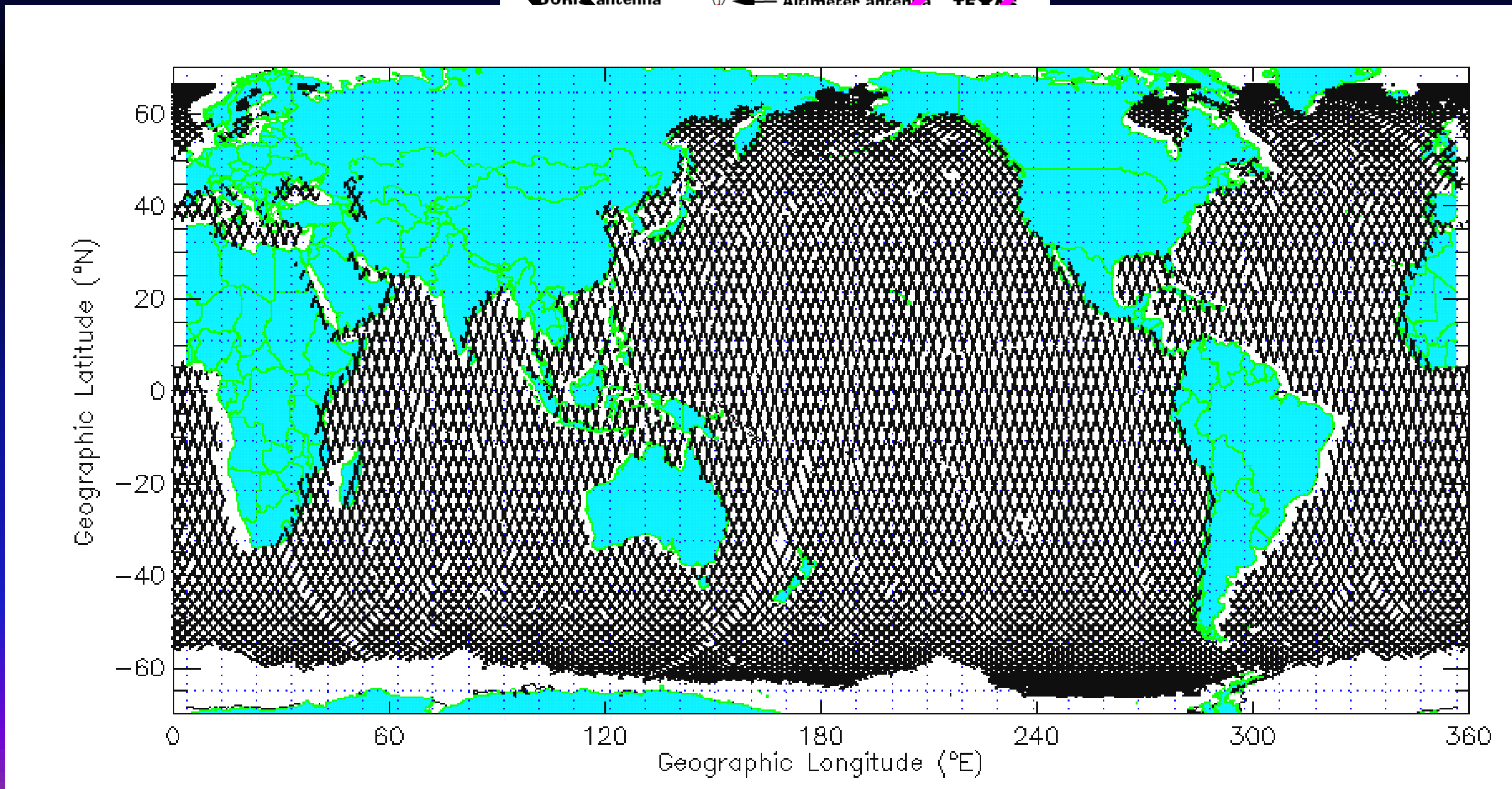
The TOPographic EXplorer (TOPEX)

Alt. : 1336 km

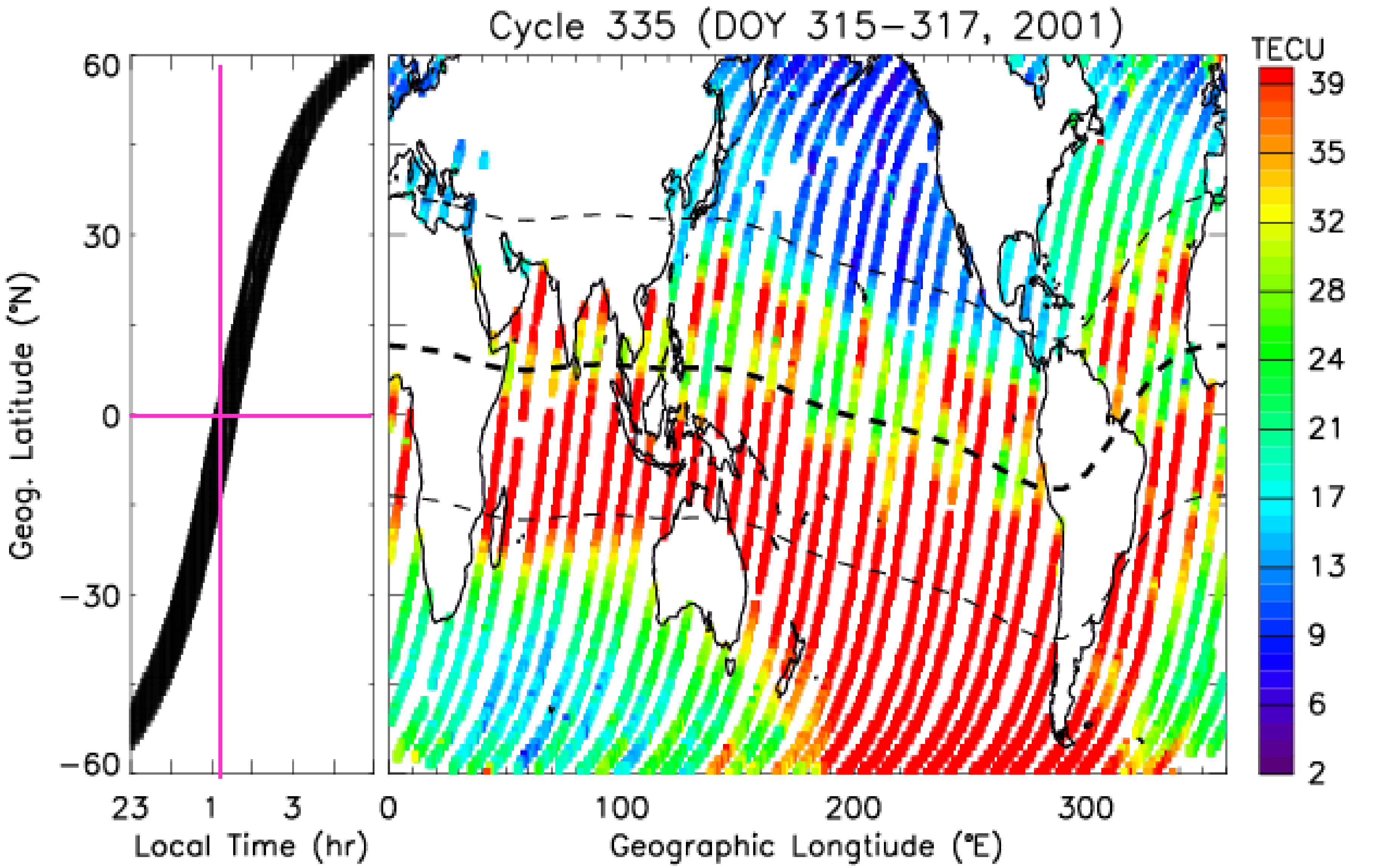
Orbit incl. 66°

Orbit per.: 1.87 hr





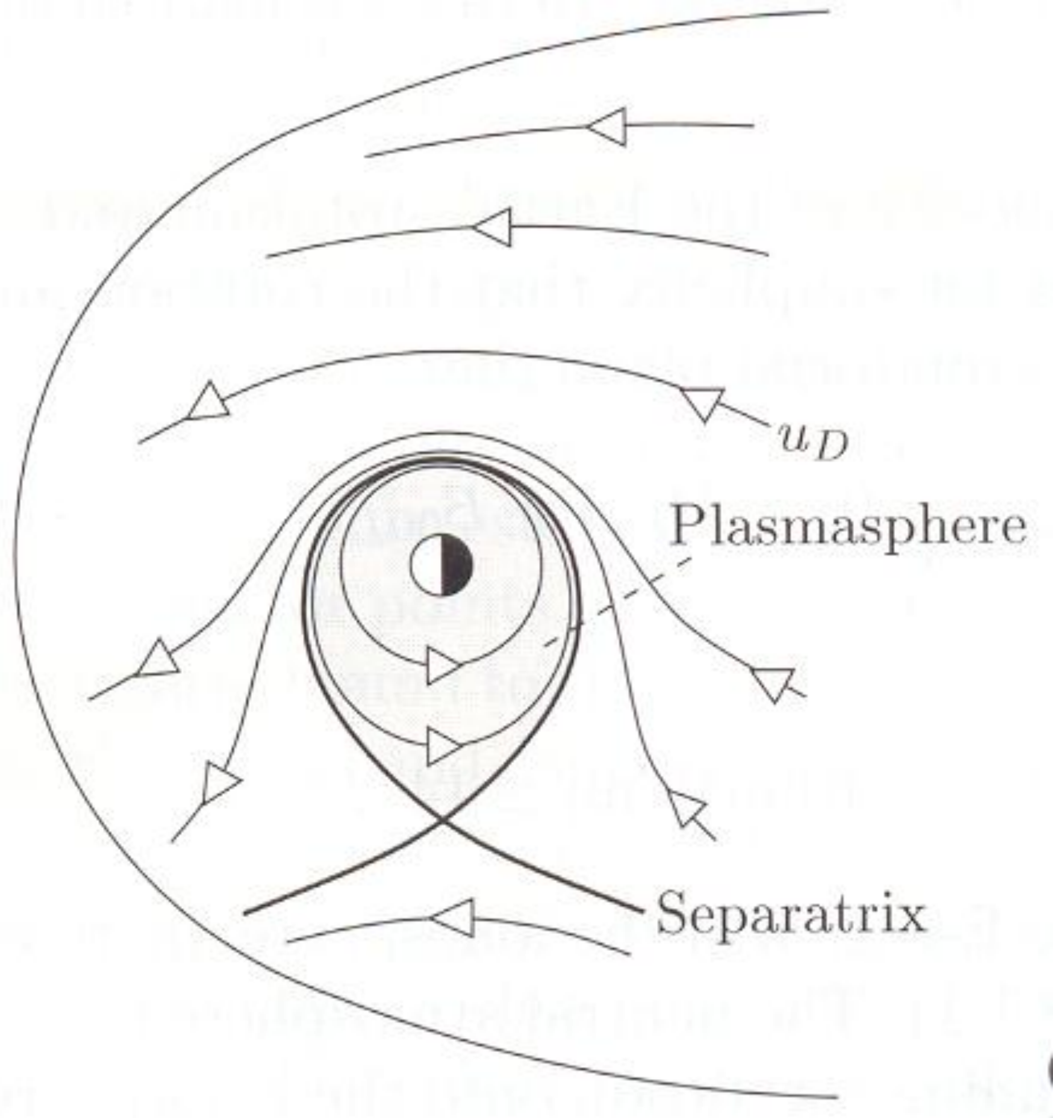
Night side TOPEX Altimeter TEC



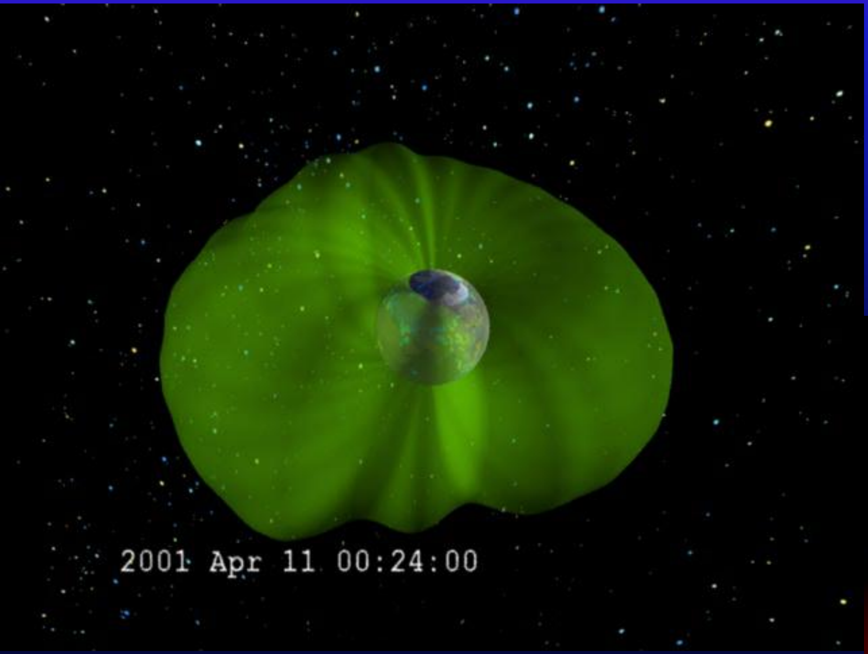
Sub-auroral Polarization Stream (SAPS): a prominent MI-coupling event

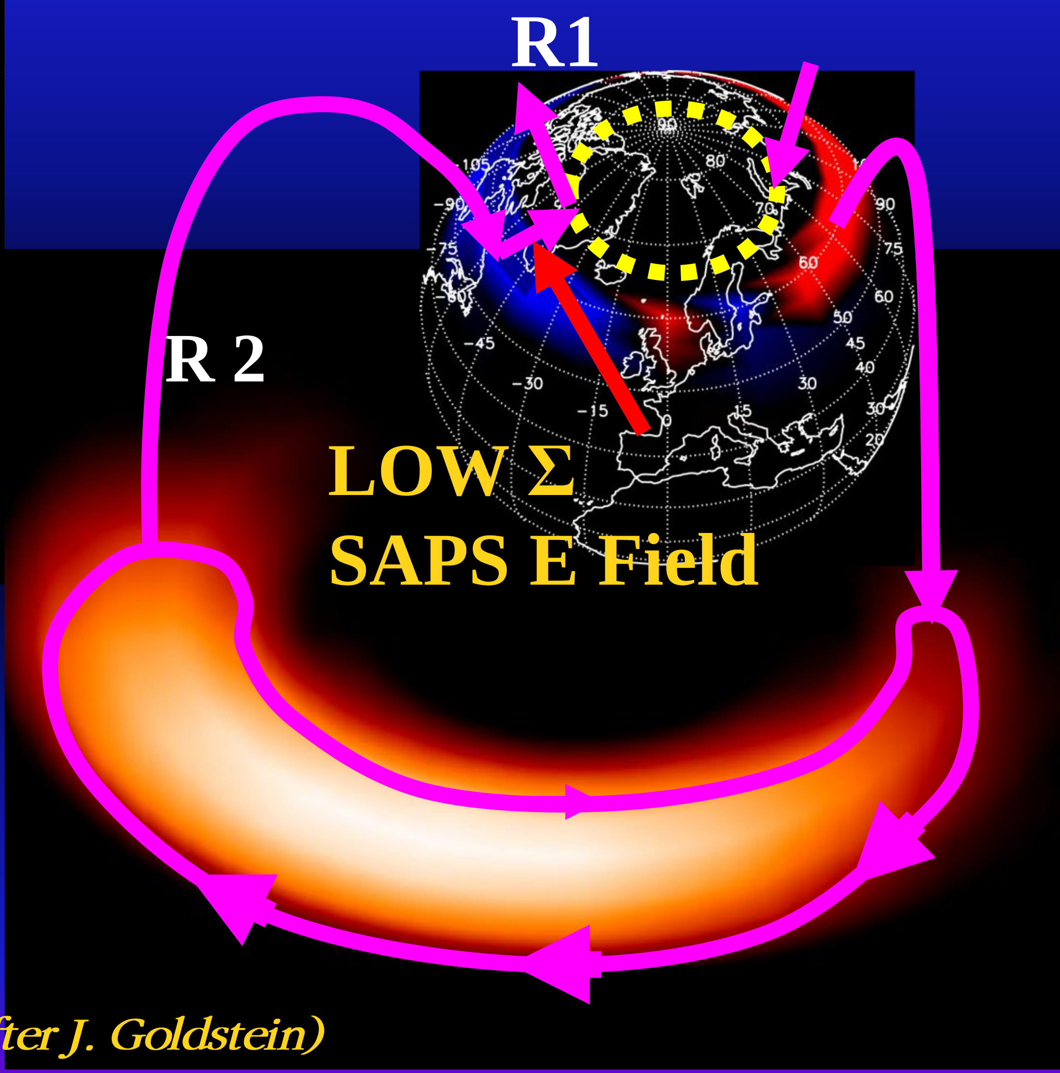
SAPS: Plasmaspheric driving force

- Corotational E-field (produced in the ionospheric E-layer and conveyed into the plasmasphere along the B-field), which is weak.
- Convection E-field (applied to the magnetosphere by its interaction with the solar wind), which is large.
- The two then superimposed and form SAPS E-field that creates a drift pattern, forming plasmaspheric plume.



SAPS effect on the ionosphere

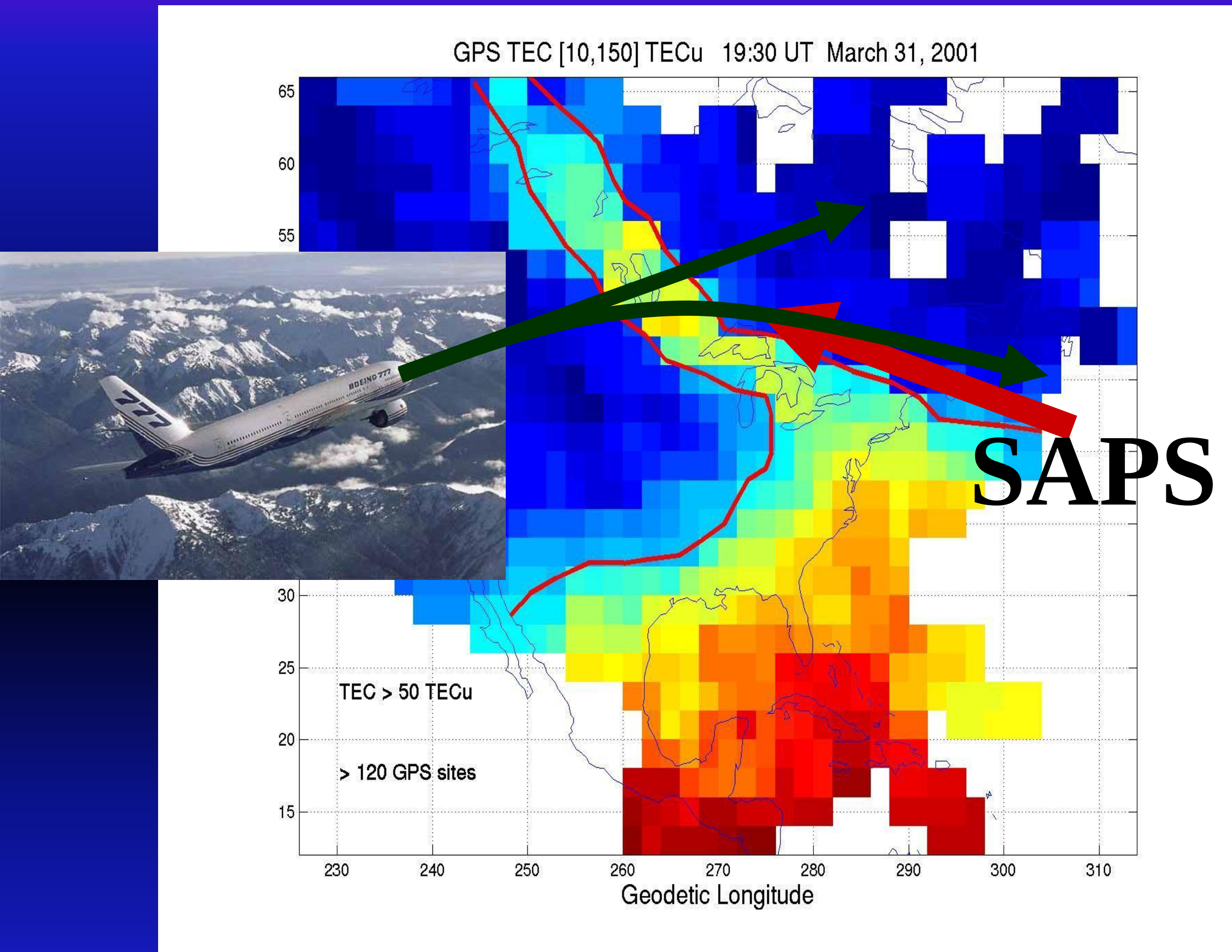




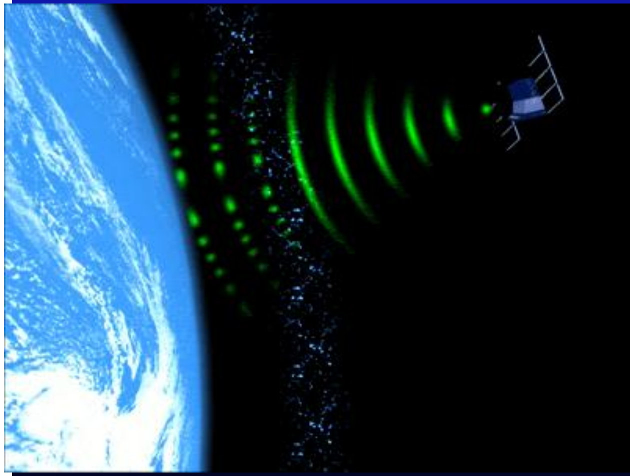
How does this come down to the ionosphere?

(after J. Goldstein)

SAPS general effect on the ionosphere



Foster et al., GRL, 2002

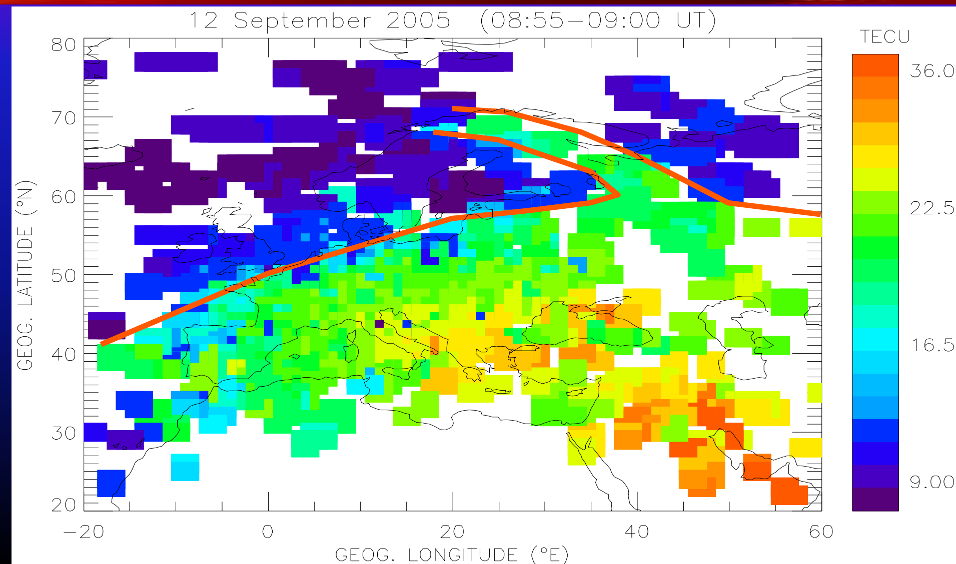


After C. Mitchell

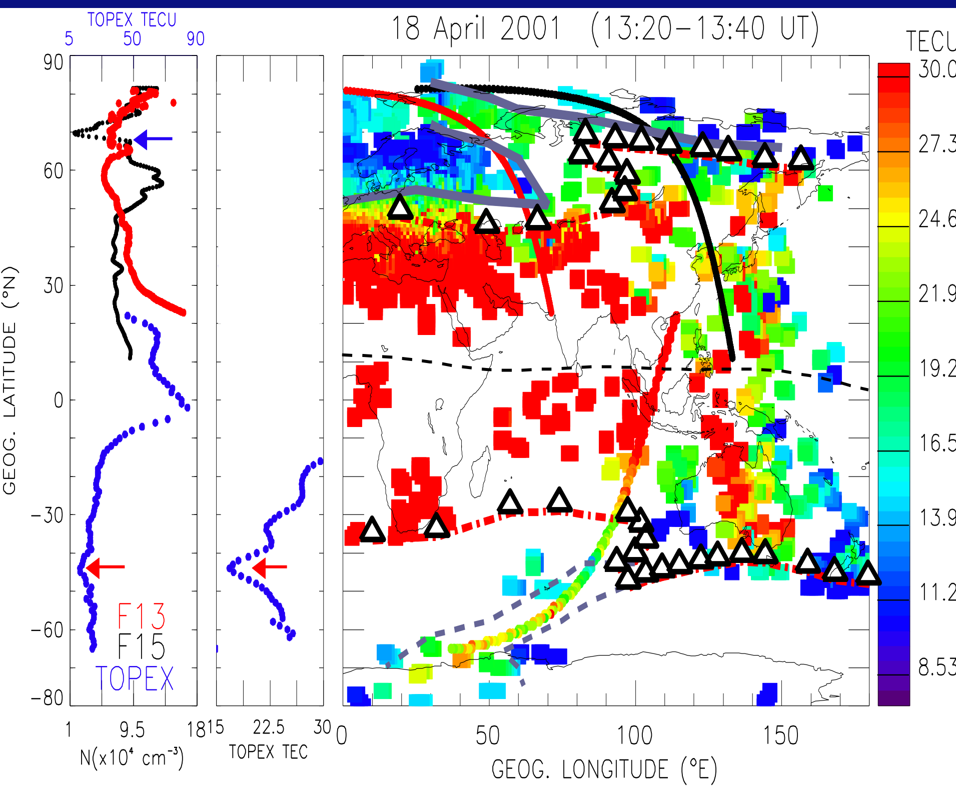
SAPS global effect on the ionosphere

Over Europe

Yizengaw et al., GRL, 2006b

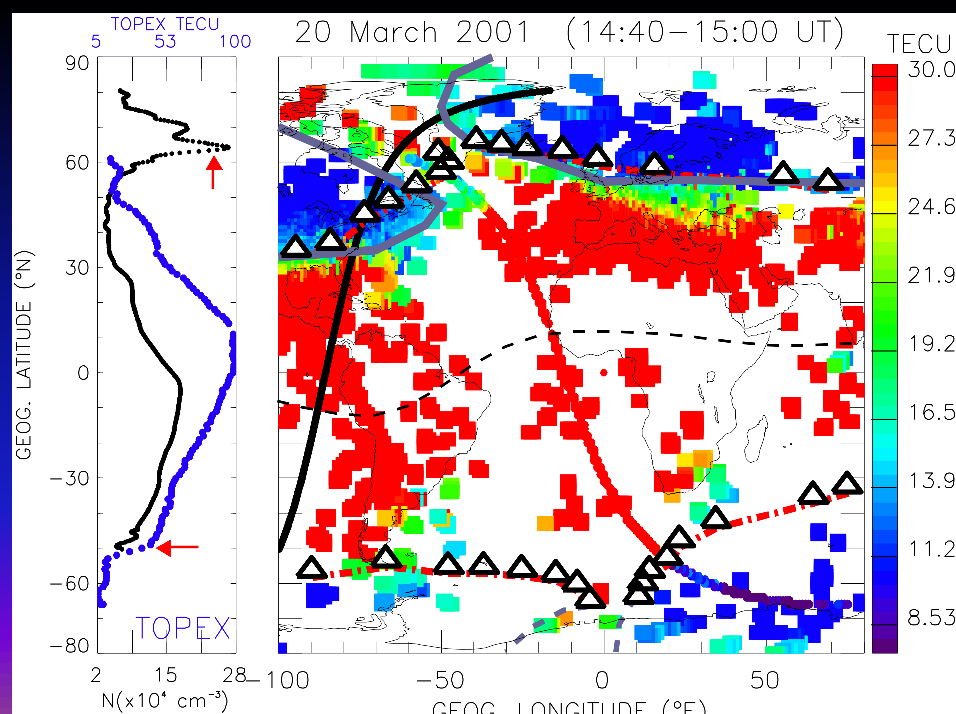


Over Asia

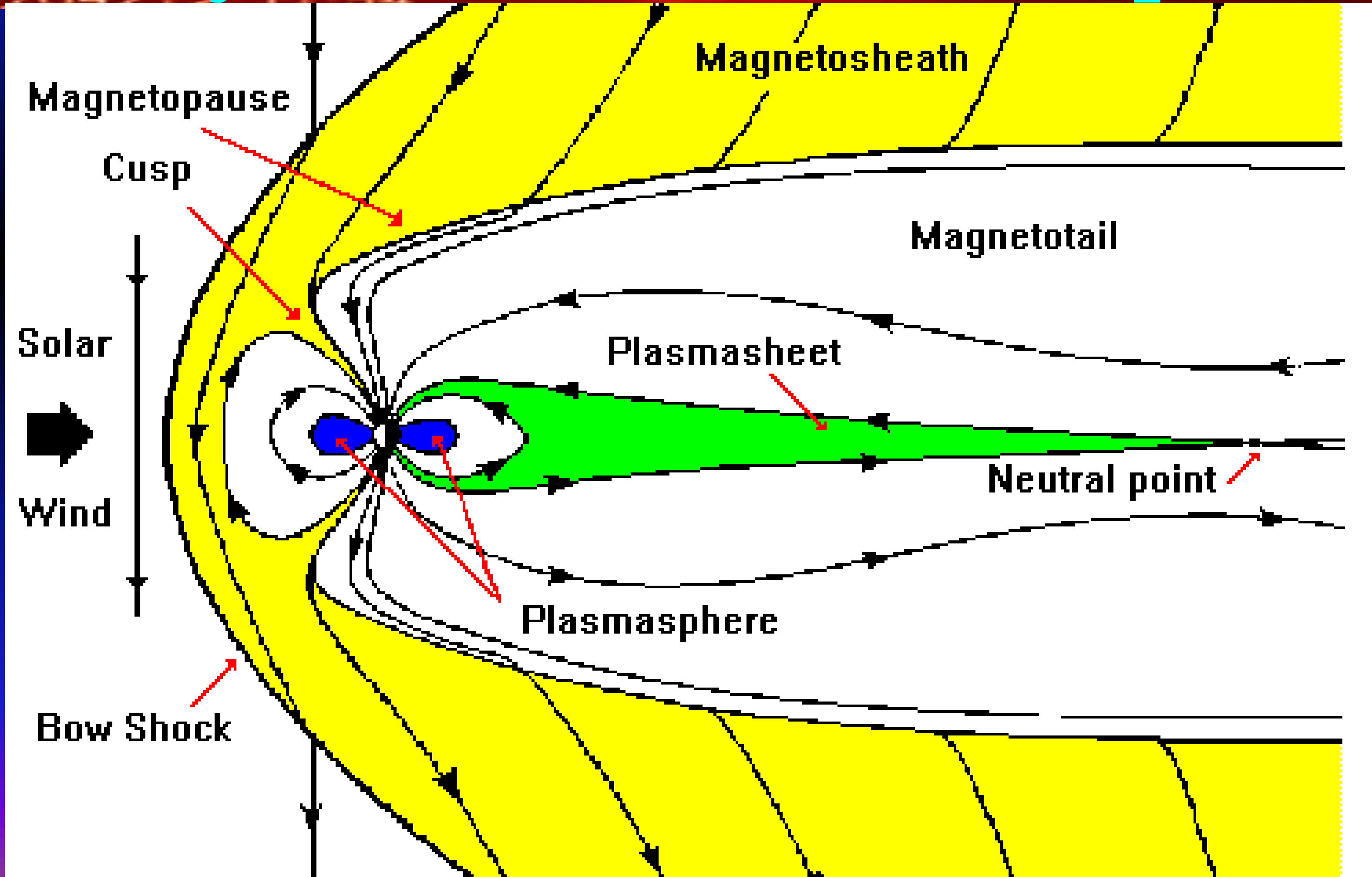


Over Atlantic Ocean

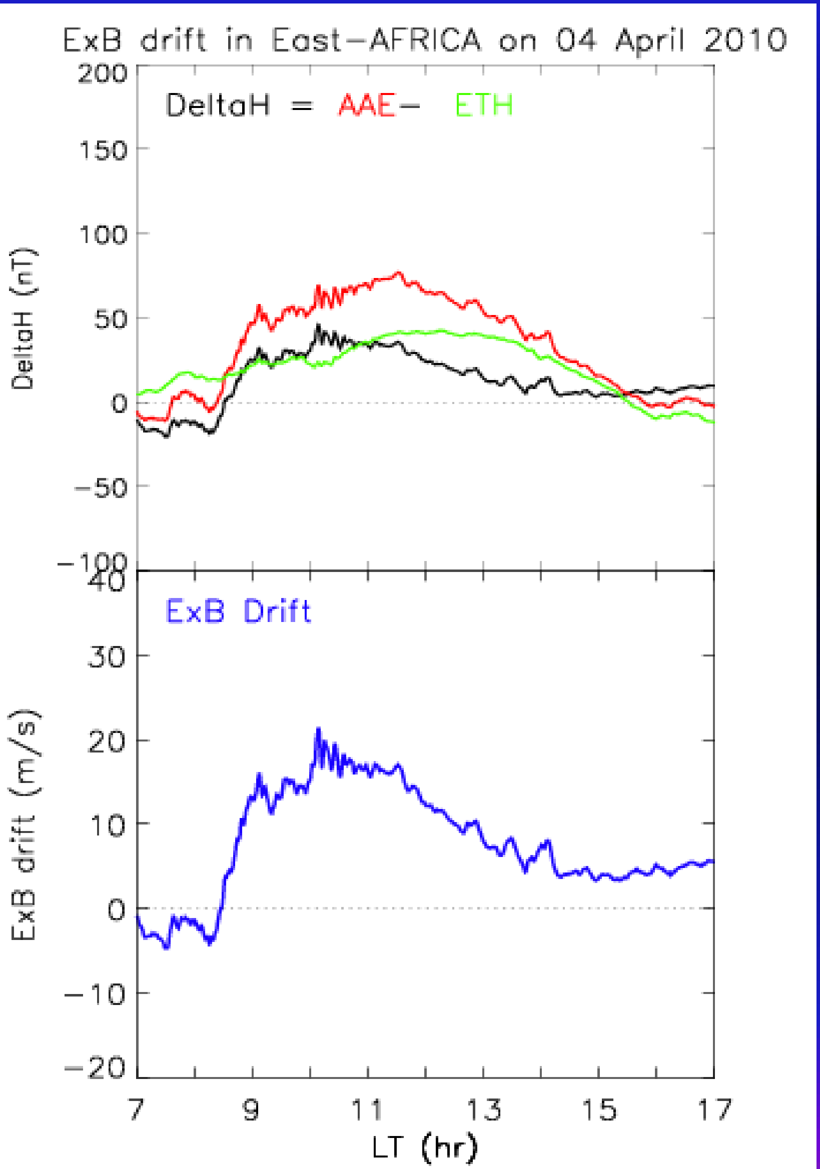
Yizengaw et al., JGR, 2008



The New Topic: The ULF wave in the magnetopause and the ionospheric density fluctuation at the equator



Equatorial EEJ/ vertical drift



- ✈ **Disturbance due to magnetospheric and penetrating, from high-latitudes, ionospheric currents**

  On H-components at the equator and off the equator

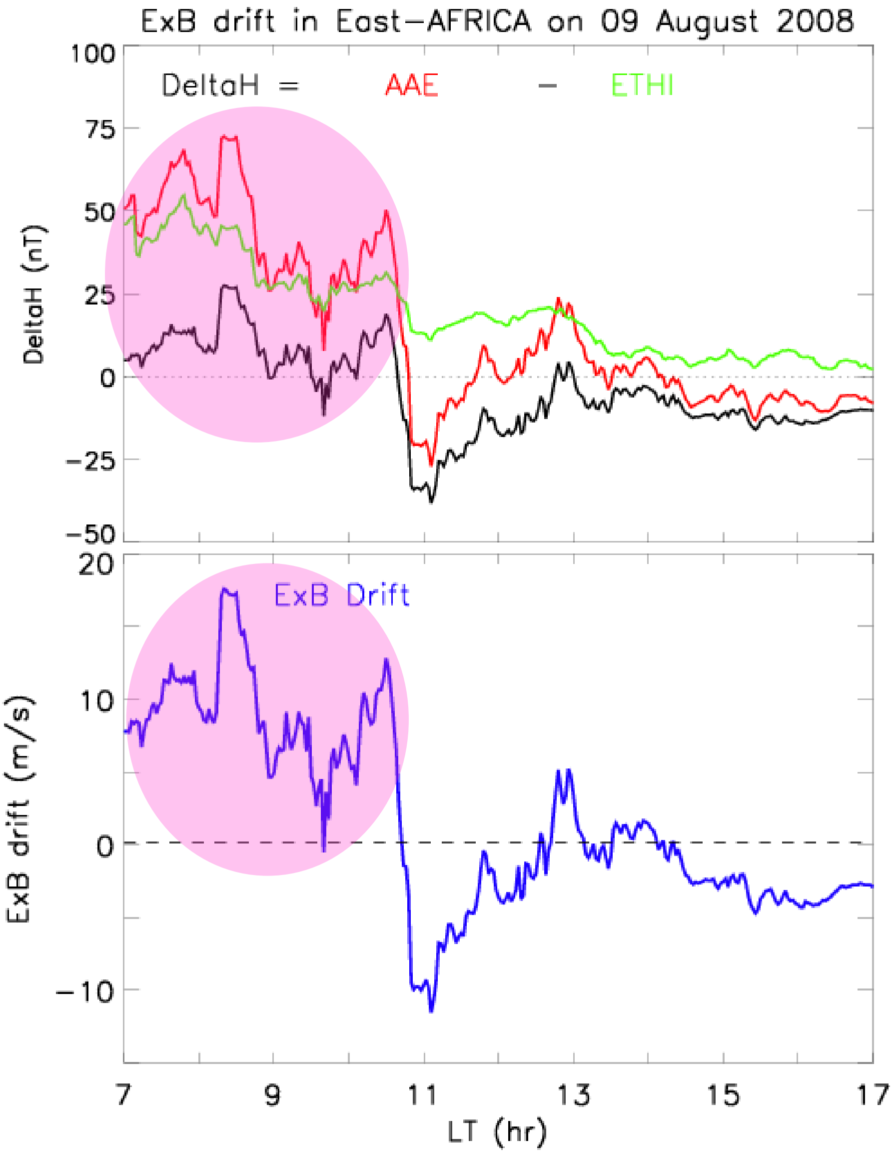
- ✈ **Disturbances due to EEJ**

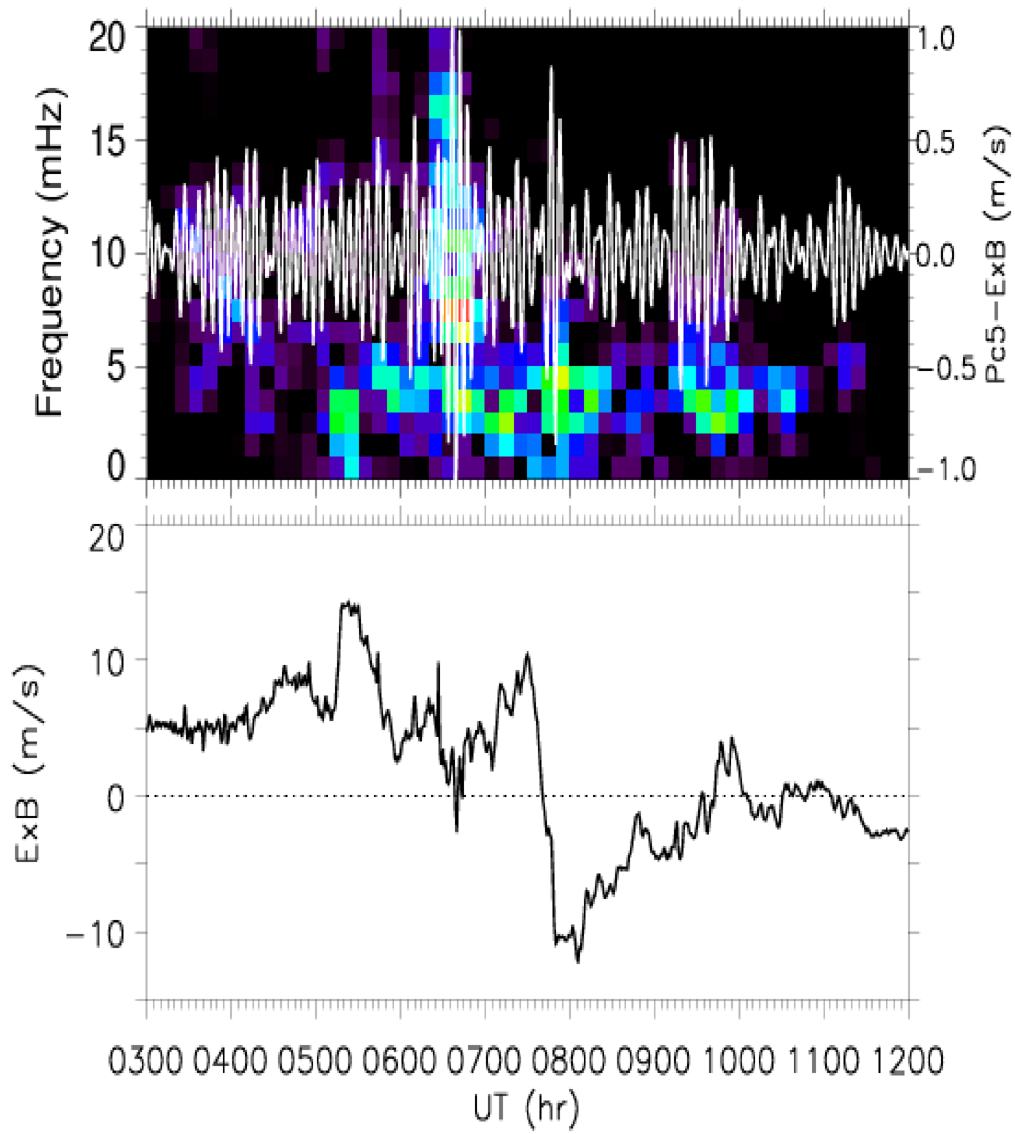
  Only on H-component at the equator

Equatorial Vertical Drift Fluctuation

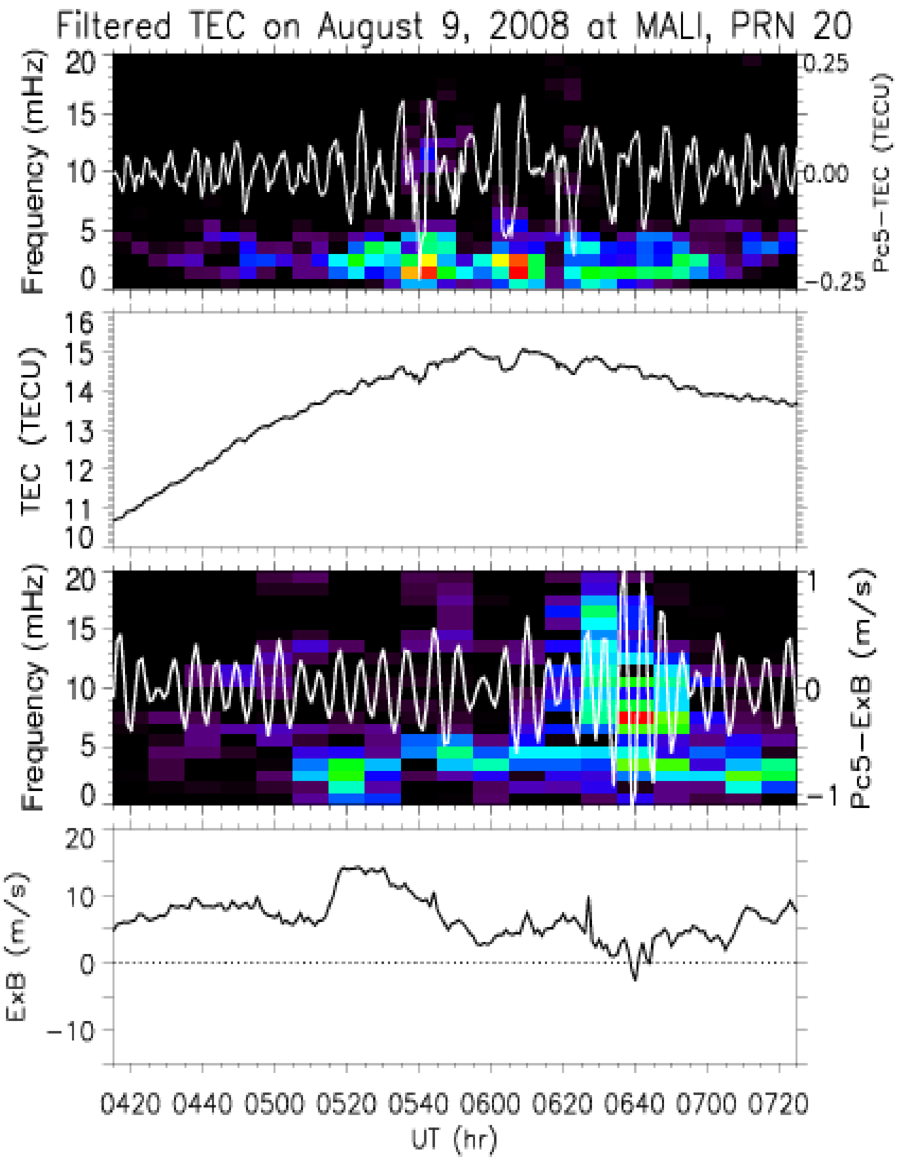
African sector

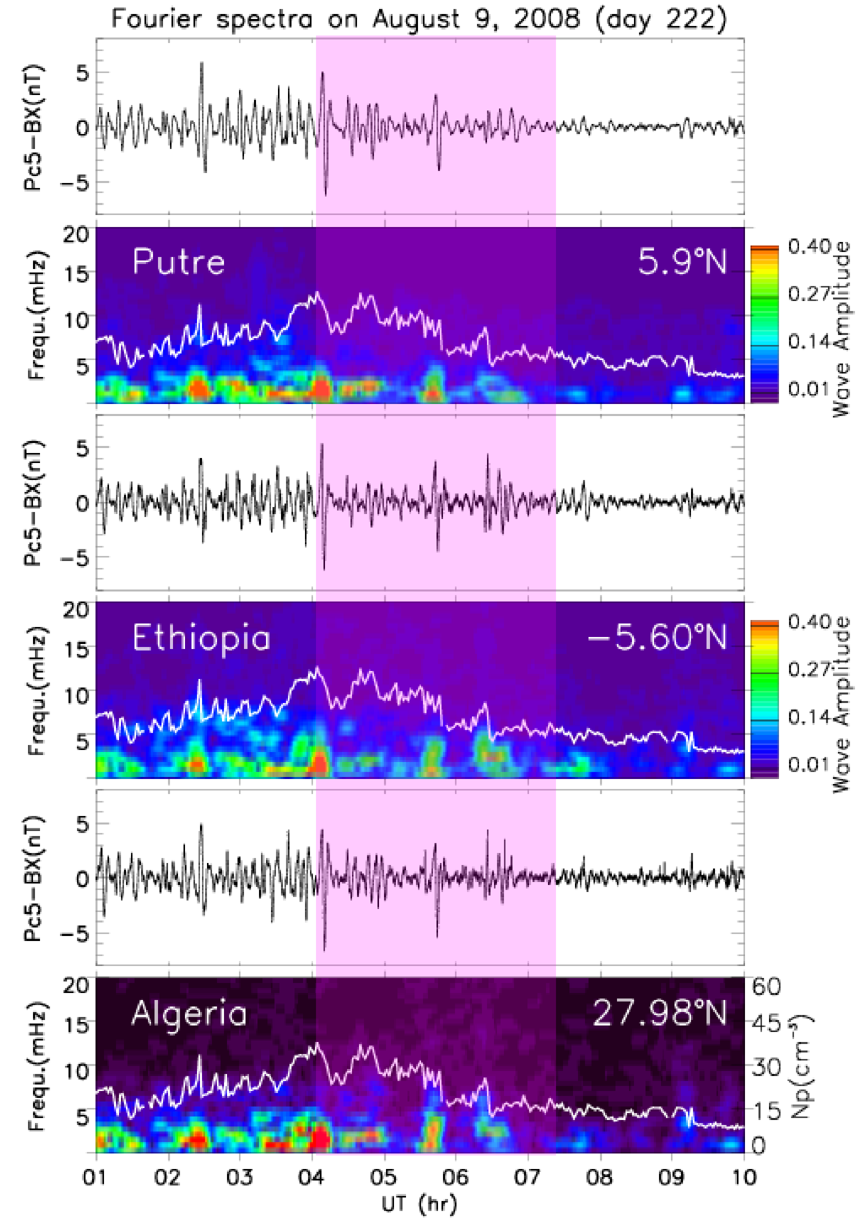
Band-pass filtered drift shows ULF wave



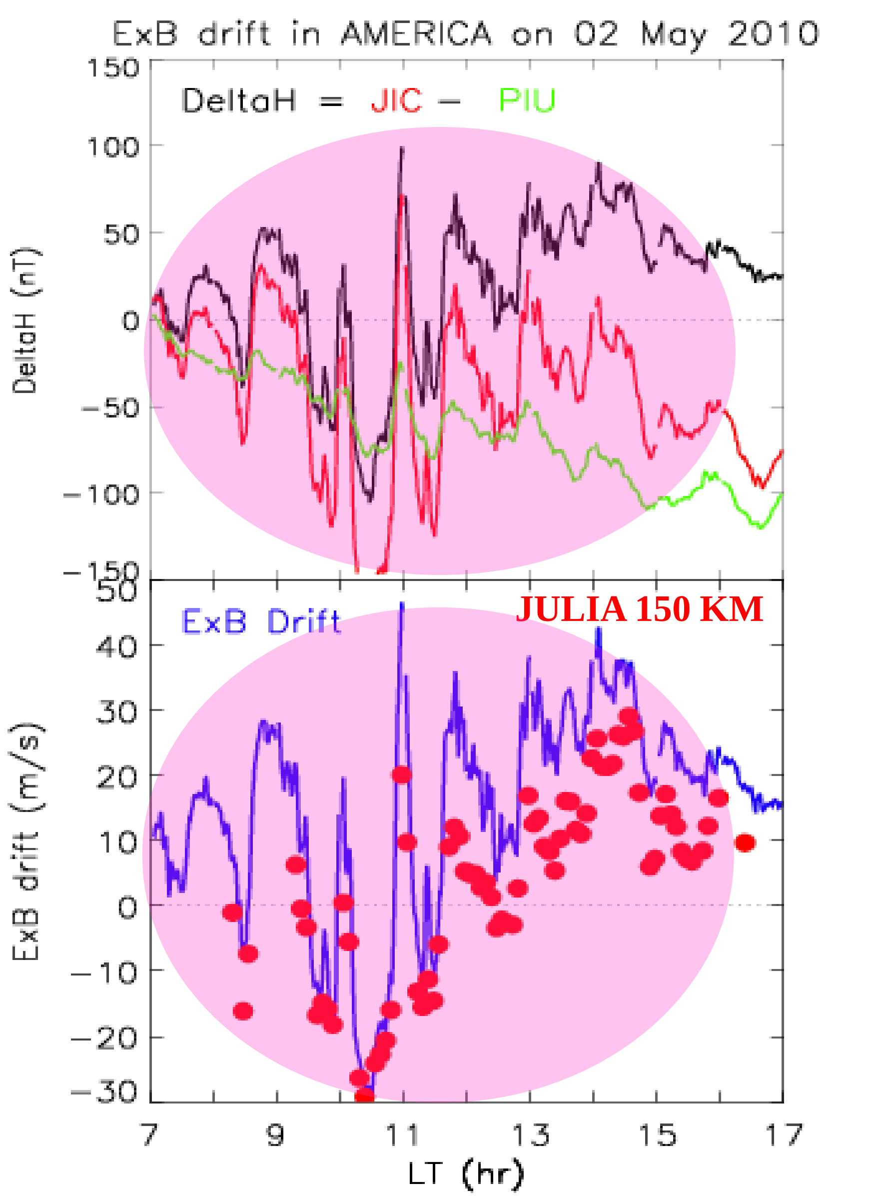


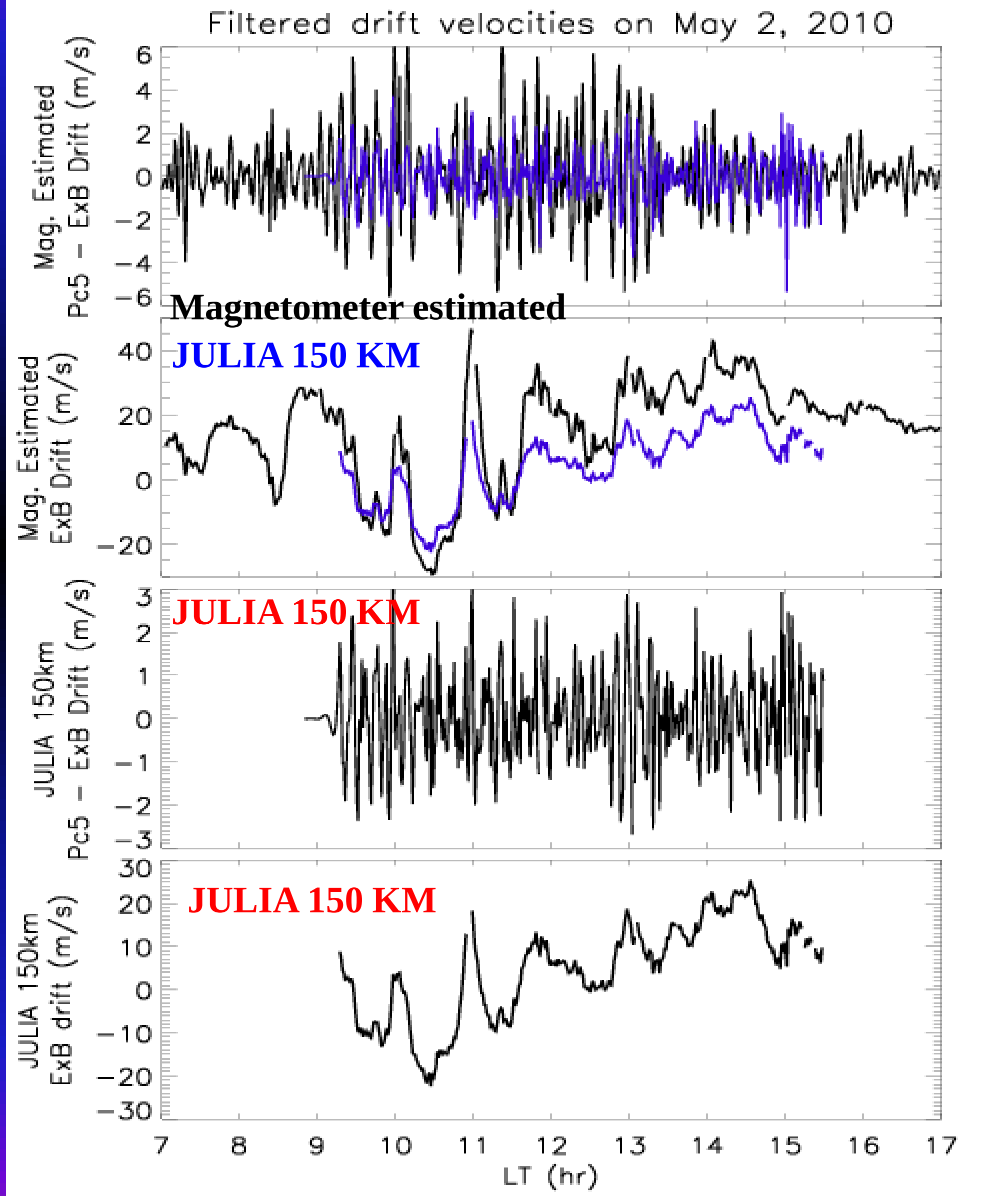
Vertical Drift and Density Fluctuation



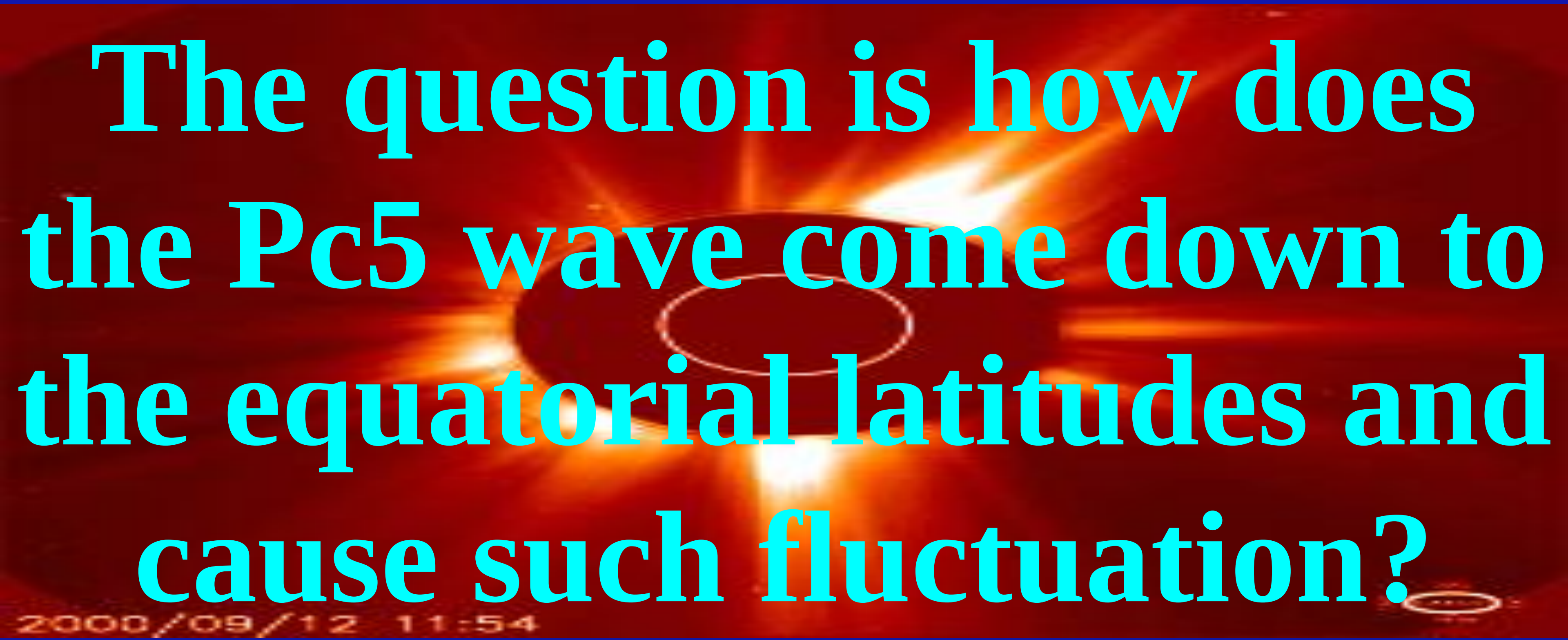


Vertical Drift and Density Fluctuation

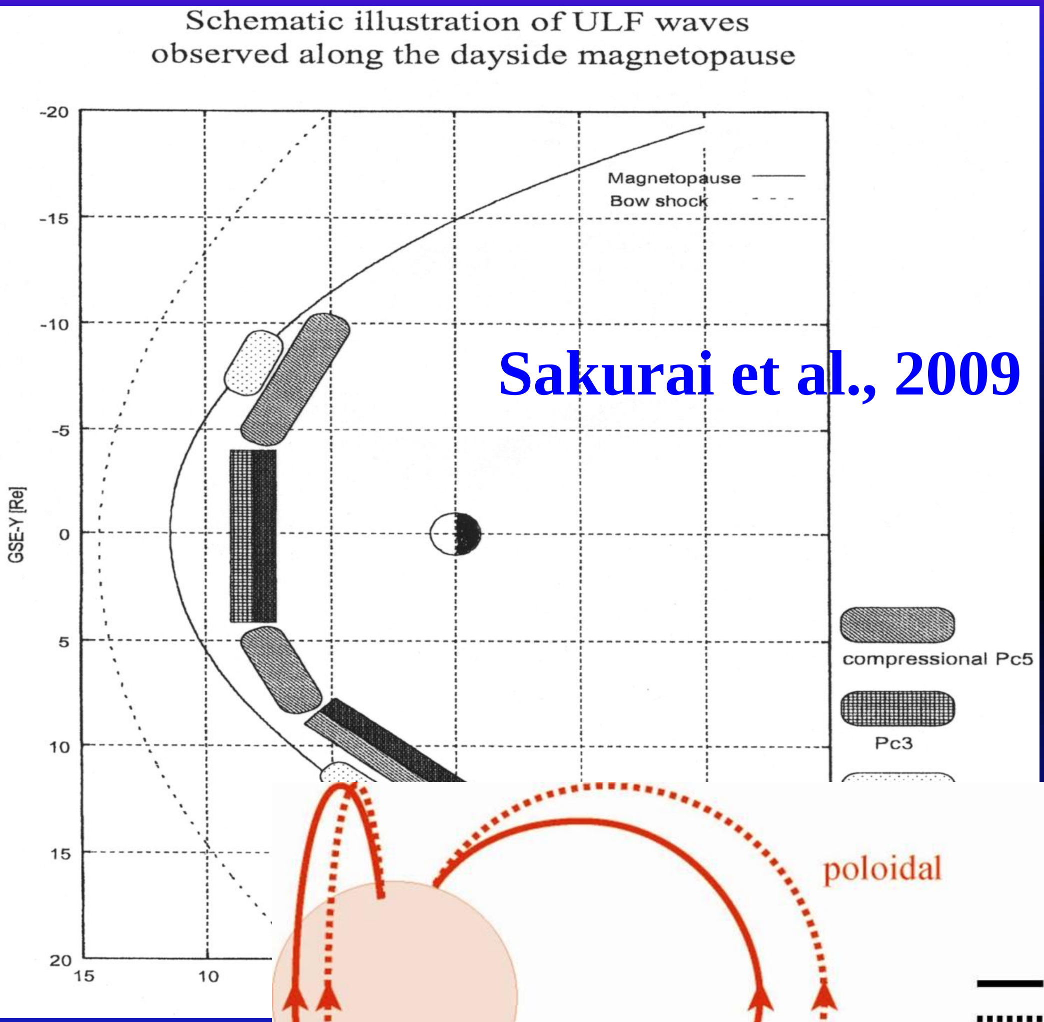




The question is how does the Pc5 wave come down to the equatorial latitudes and cause such fluctuation?

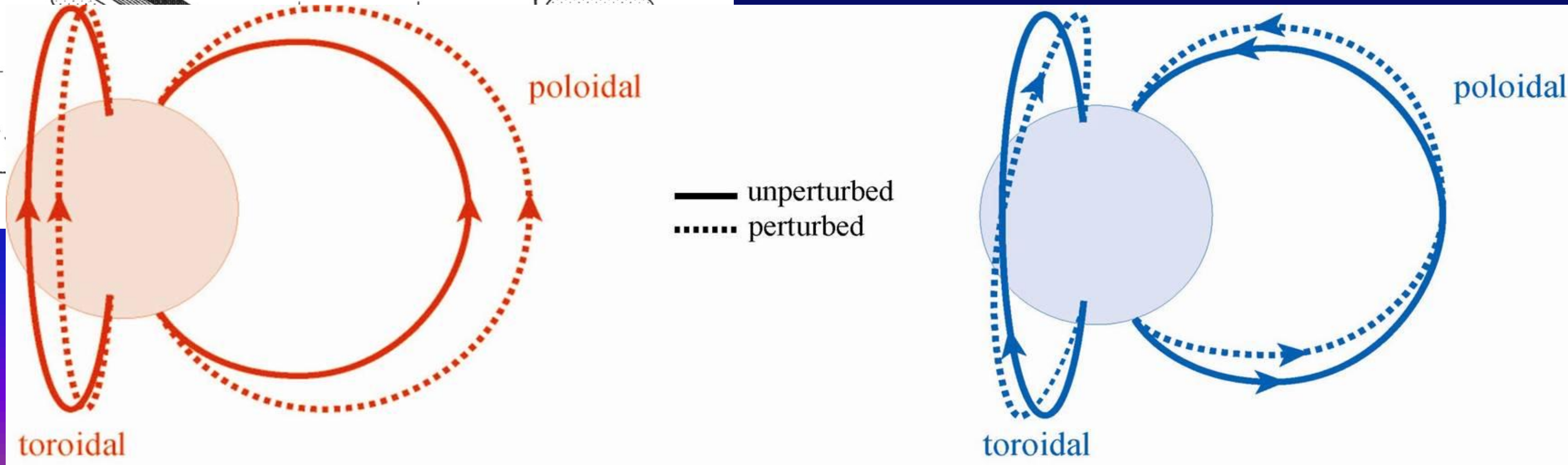


Schematic Illustration of ULF waves

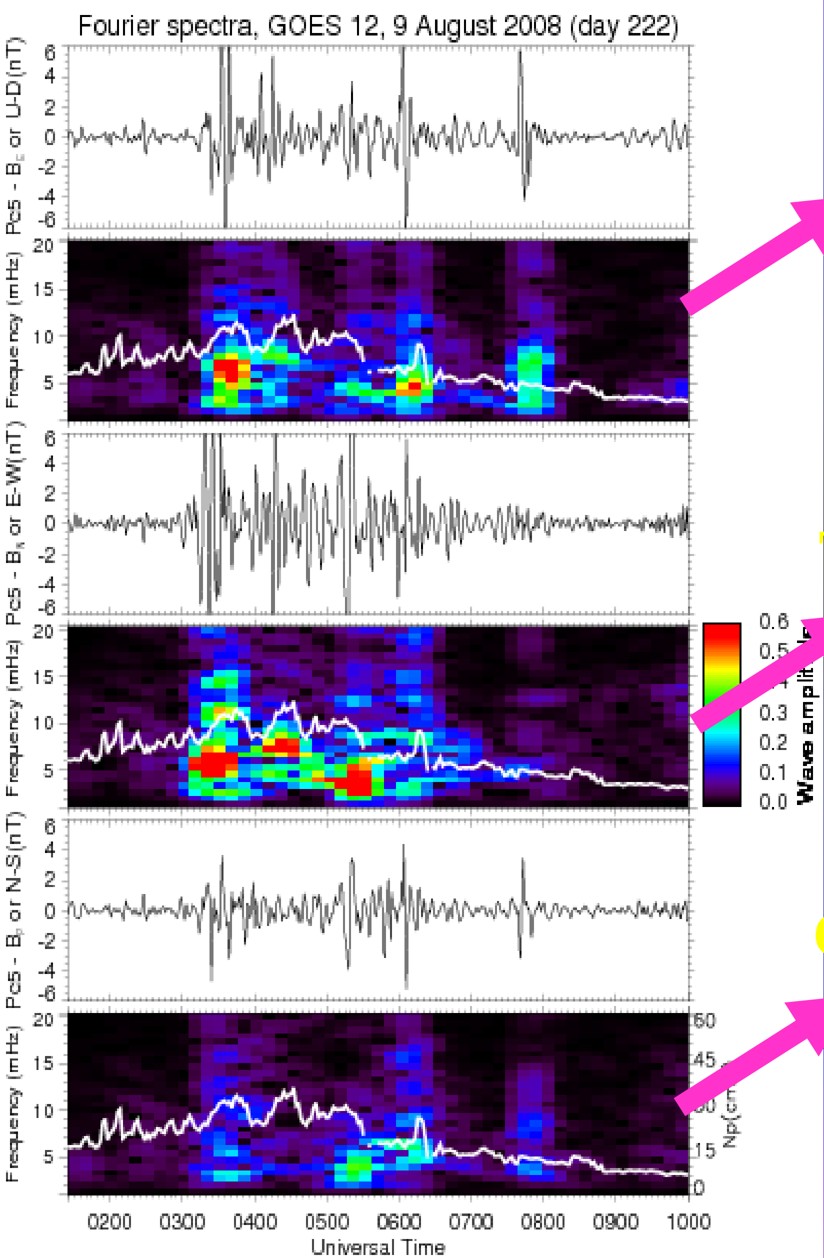


Sakurai et al., 2009

ULF wave in the range of Pc5 oscillations (1-7 mHz) can be observed over a wide range of local time, and near the flanks the compressional Pc5 oscillations occurs frequently in association with the magnetic impulses.



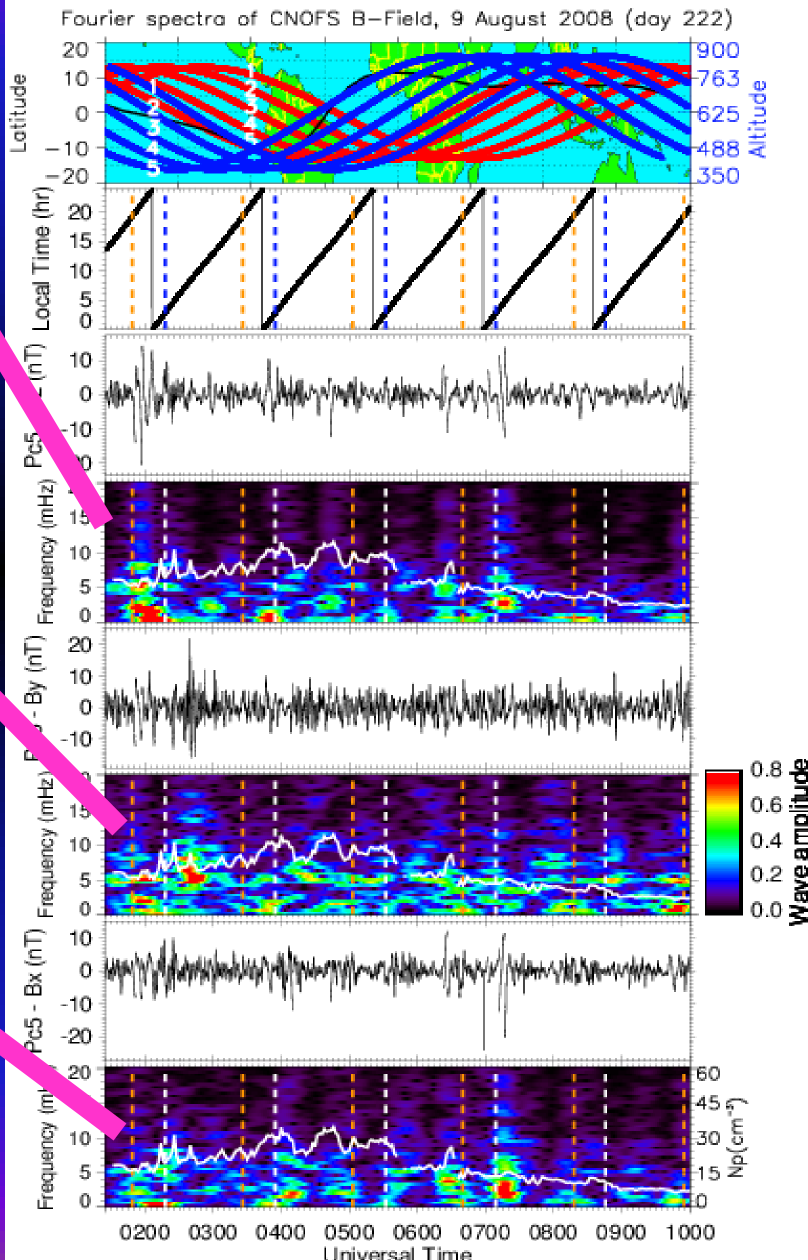
Eveidence ULF Pc5 waves in space



Radial

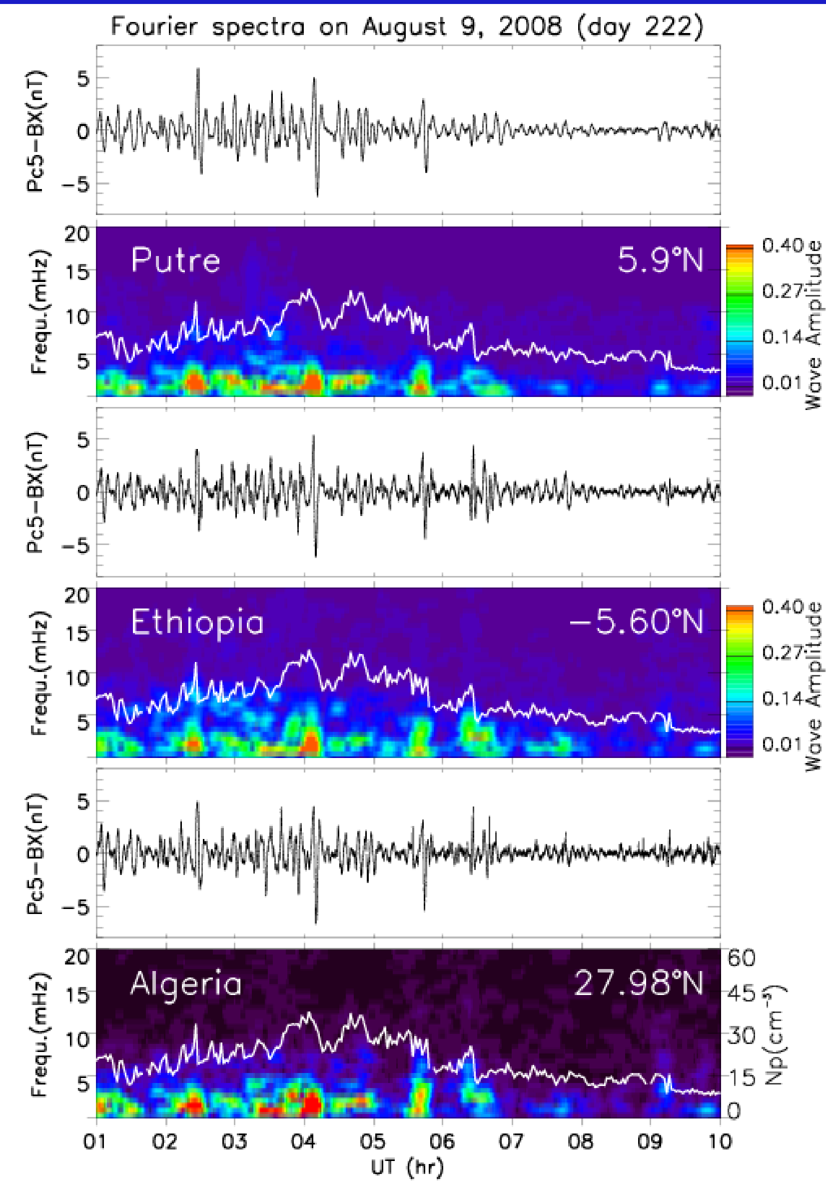
Toroidal mode

Compressional mode

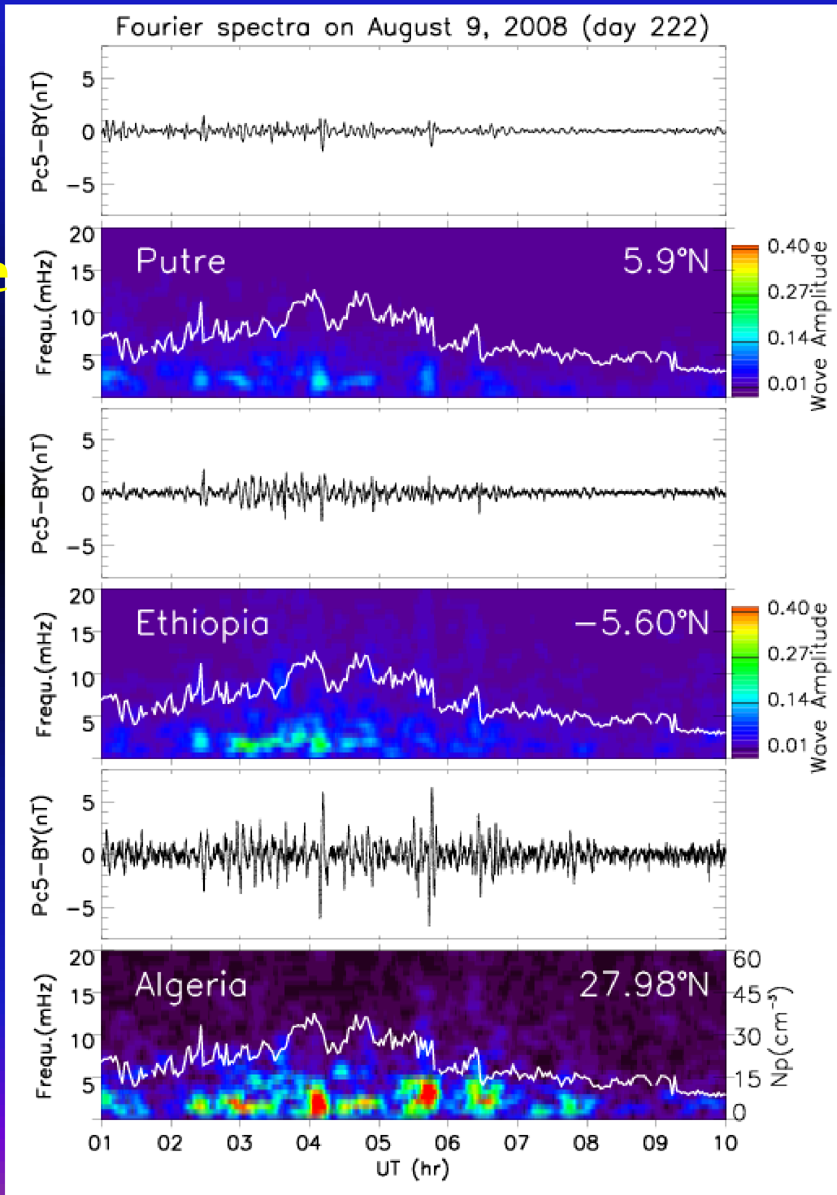


ULF Pc5 waves on the ground

Toroidal mode



Compressional mode

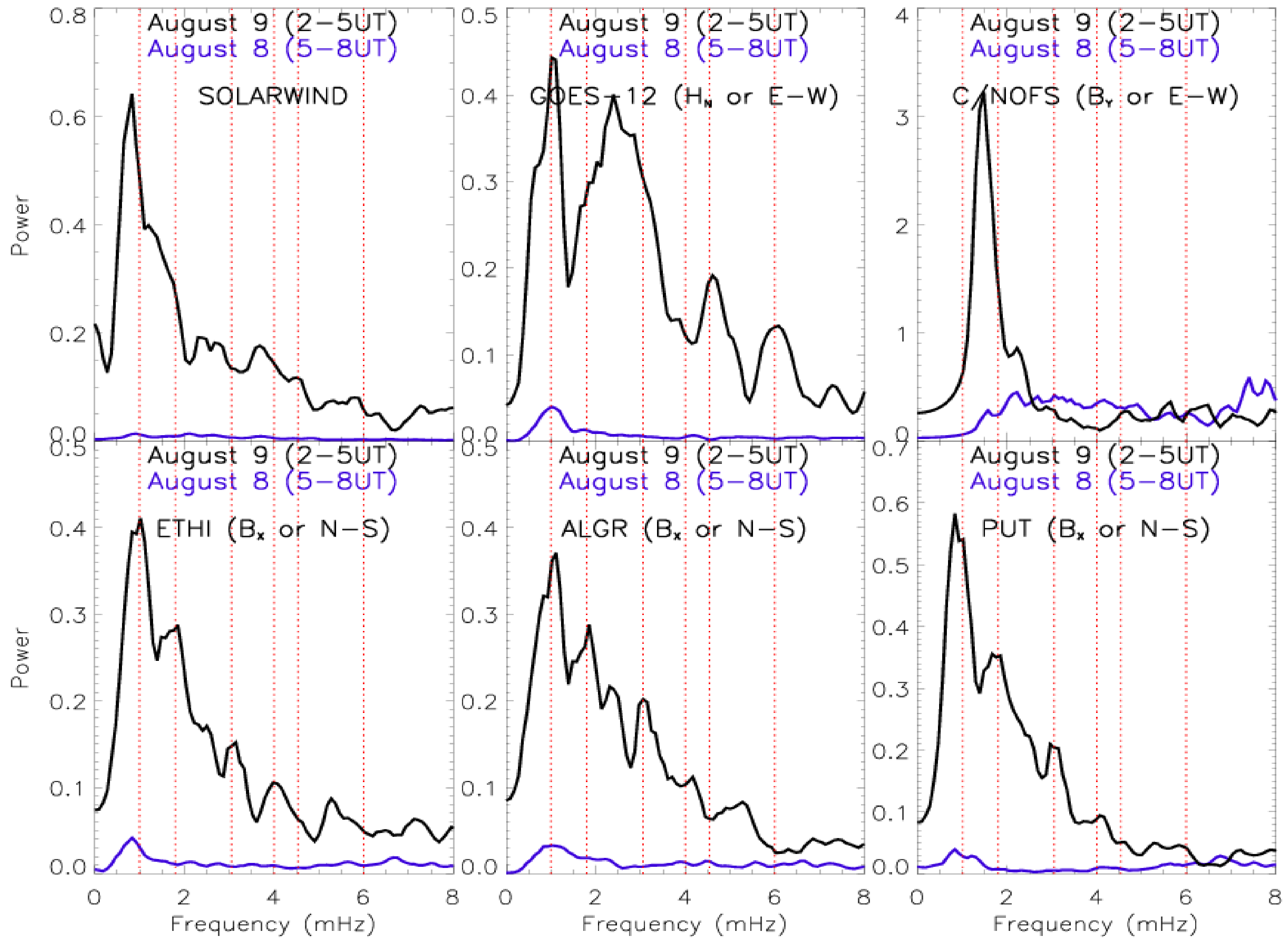


Night side

Day side

Day side

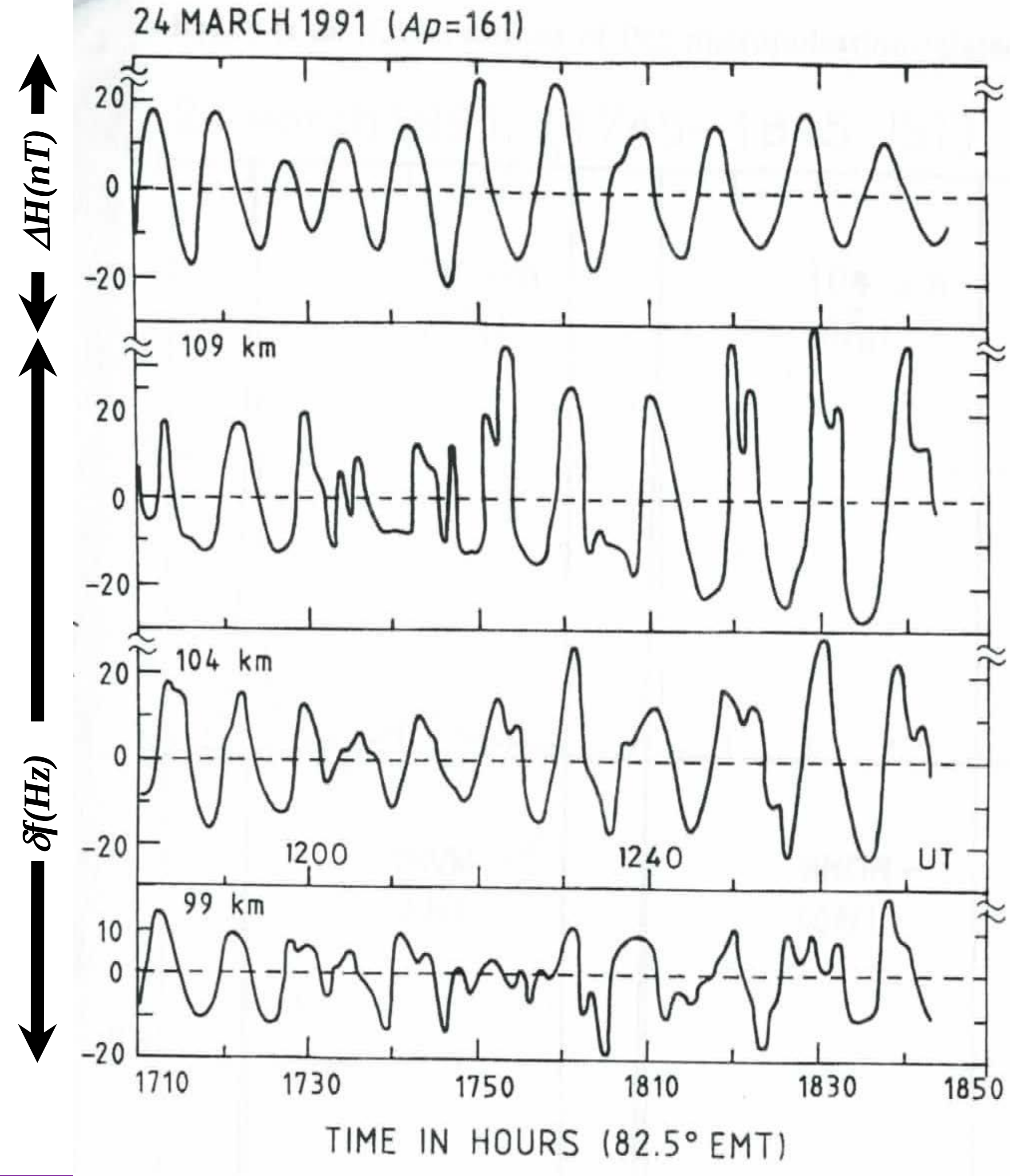
What triggers the ULF Pc5 waves



ULF wave and density irregularity correlation

Time series of Doppler frequency variation at three different altitudes, observed by 54.95 MHz coherent backscatter radar!

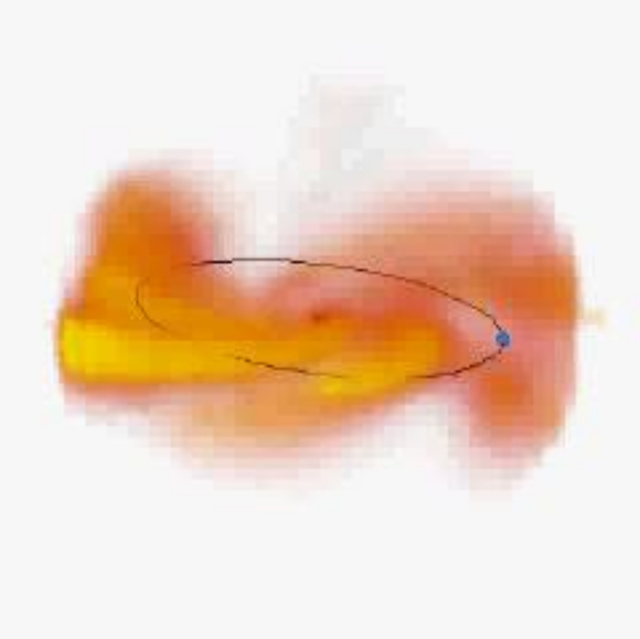
(Reddy et al., AG, 1994)



Why space weather/MI coupling so important? (summary)

Solar wind-Earth interaction

- **Generates Electrical Currents and cause a power outage, energizes particles (radiation), moves plasma and affect our communication and navigation systems**
- **heat the upper atmosphere, causing it to expand, increasing drag on LEO satellites**



The 2008 US National Research Council report estimated the cost if a September 1859 sized CME hit us; first it could take us 10 years to recover, and cost could be between $1 trillion and $2 trillion (in the first year alone) to repair the damage.

Let's just hope, with the NASA's Solar Probe Plus, we'll have plenty of warning before the next major event overloads the planet.

In March 2012, the British government declare that space weather is one of the greatest threats to the country

"Severe space weather can cause disruption to a range of technologies and infrastructure, including communications systems, electronic circuits and power grids."

Cabinet Office's National Risk of Civil Emergencies report

2nd part will follow

AMBER Magnetometers Network and Longitudinal Differences of Equatorial Electrodynamics and Ionospheric Vertical Density Distribution

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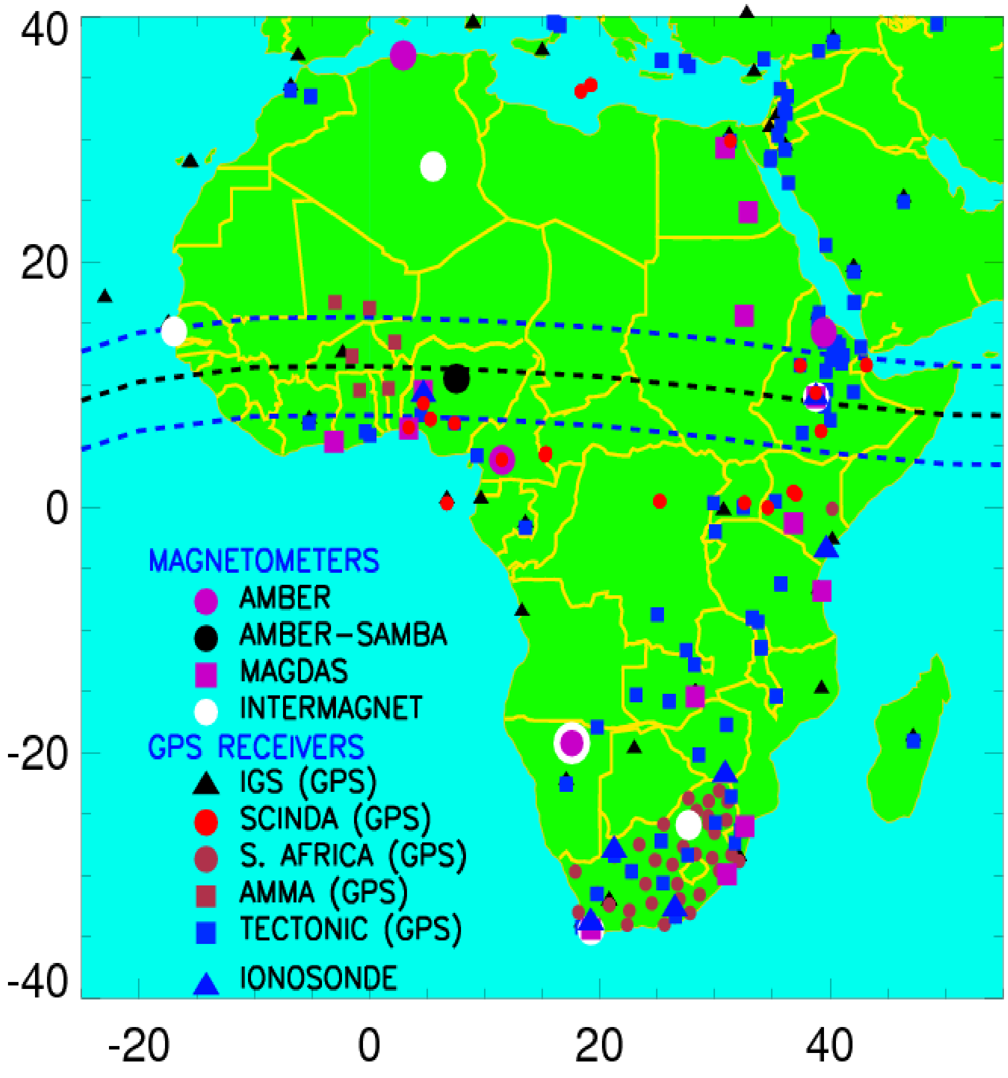
Institute for Scientific Research, Boston College

Team Members: M. Moldwin (UM); E. Zesta (AFRL); B. Damtie (BDU, Ethiopia); A. Mebrhtu (MU, Ethiopia); F. Anad (CRAAG, Algeria); C. Mabene (UY, Cameroon); P. Kotze (SANSA, S. Africa) ; and B. Rabiu (NASRDA. Nigeria)

Outline

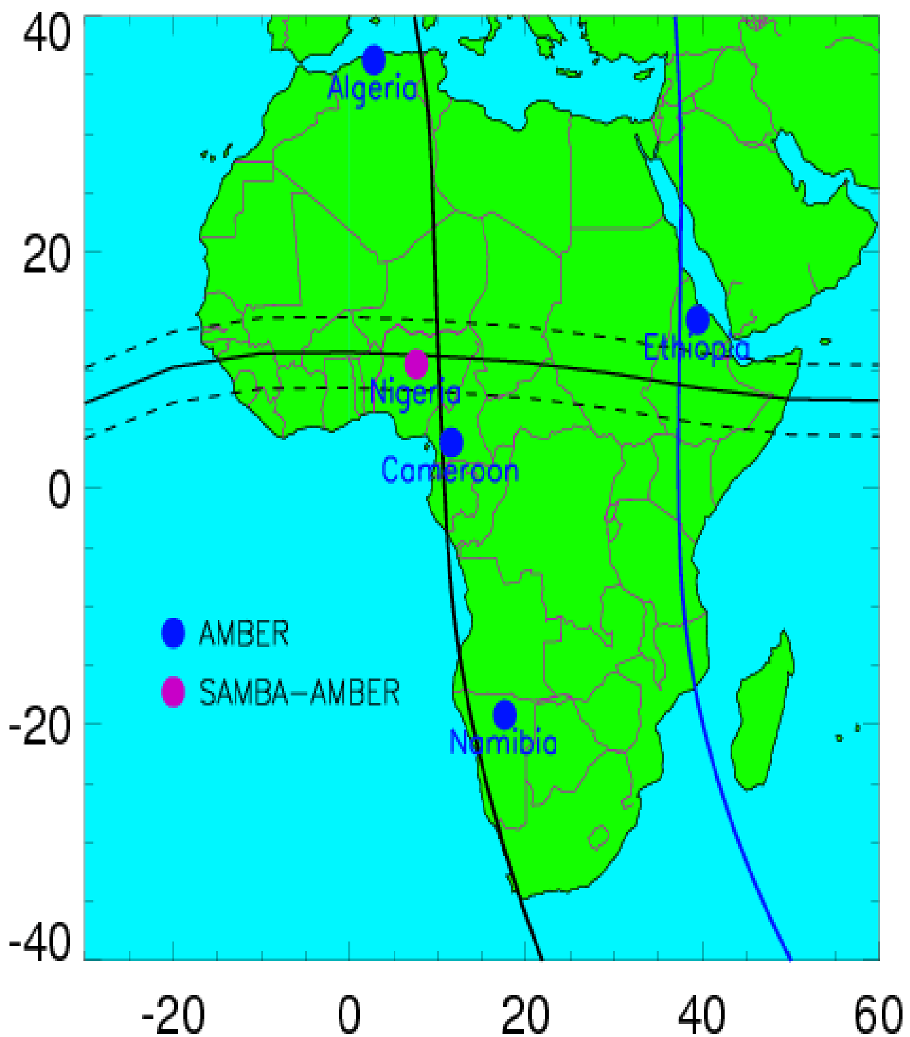
Instruments Network: Present



- **AMBER magnetometer array**
- **EEJ (ExB drift) estimation**
- **Vertical density structures using tomography**
- **Day-to-day variability of the ionosphere**

Objective of AMBER magnetometer Array

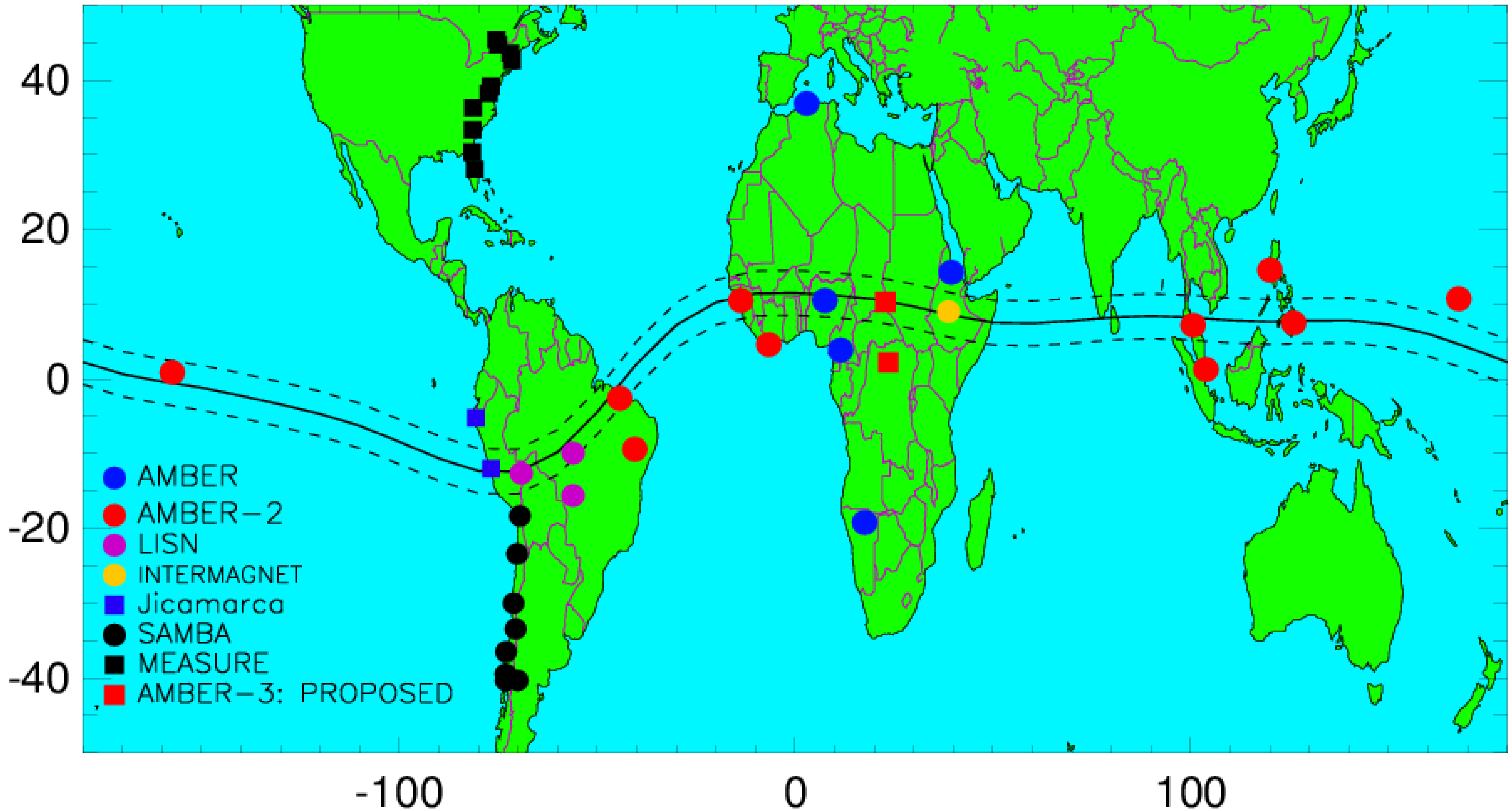
AMBER (African Meridian B-field Education and Research)



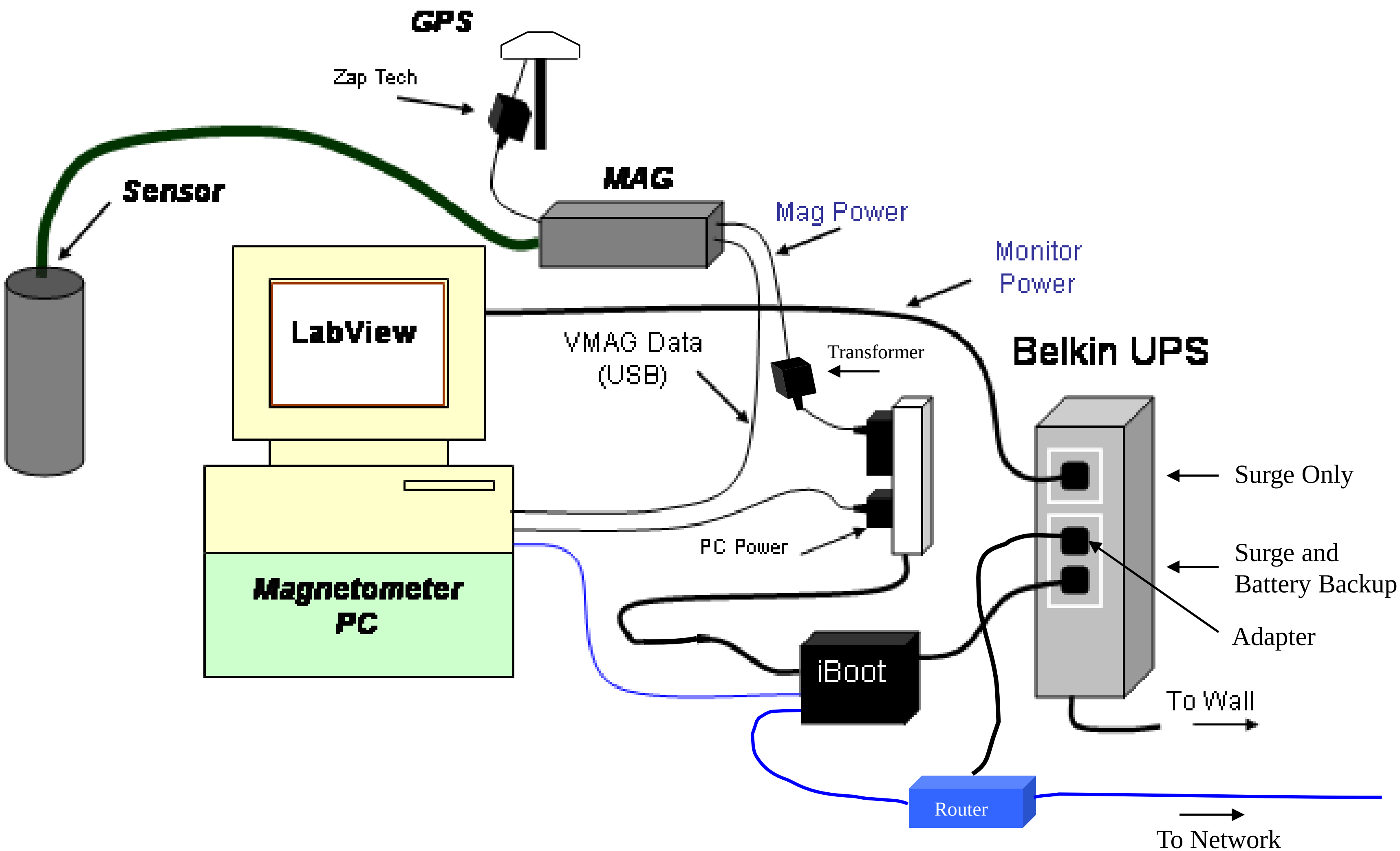
- **the processes governing electrodynamics of the equatorial ionosphere as a function of local time, longitude, magnetic activity, and season, and**
- **ULF pulsation strength and its connection with equatorial electrojet strength at low/mid-latitude regions.**

AMBER and other magnetometer networks

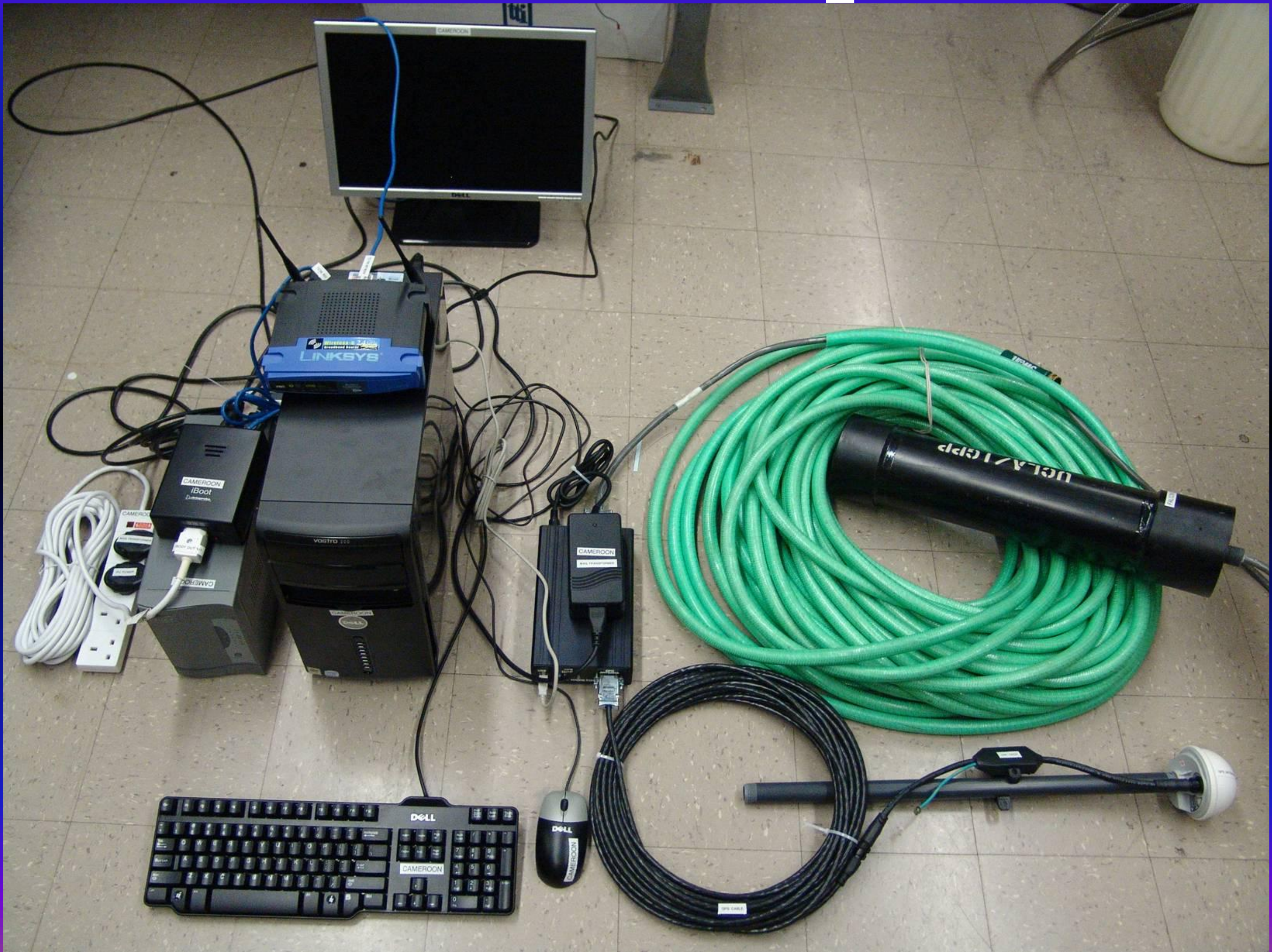
- **AMBER PI: Endawoke Yizengaw**
- **LISN PI: Cesar Valladeres**
- **SAMBA PI: Eftyhia Zesta**
- **MEASURE PI: Mark Moldwin**



Mag/Sensor Setup Diagram



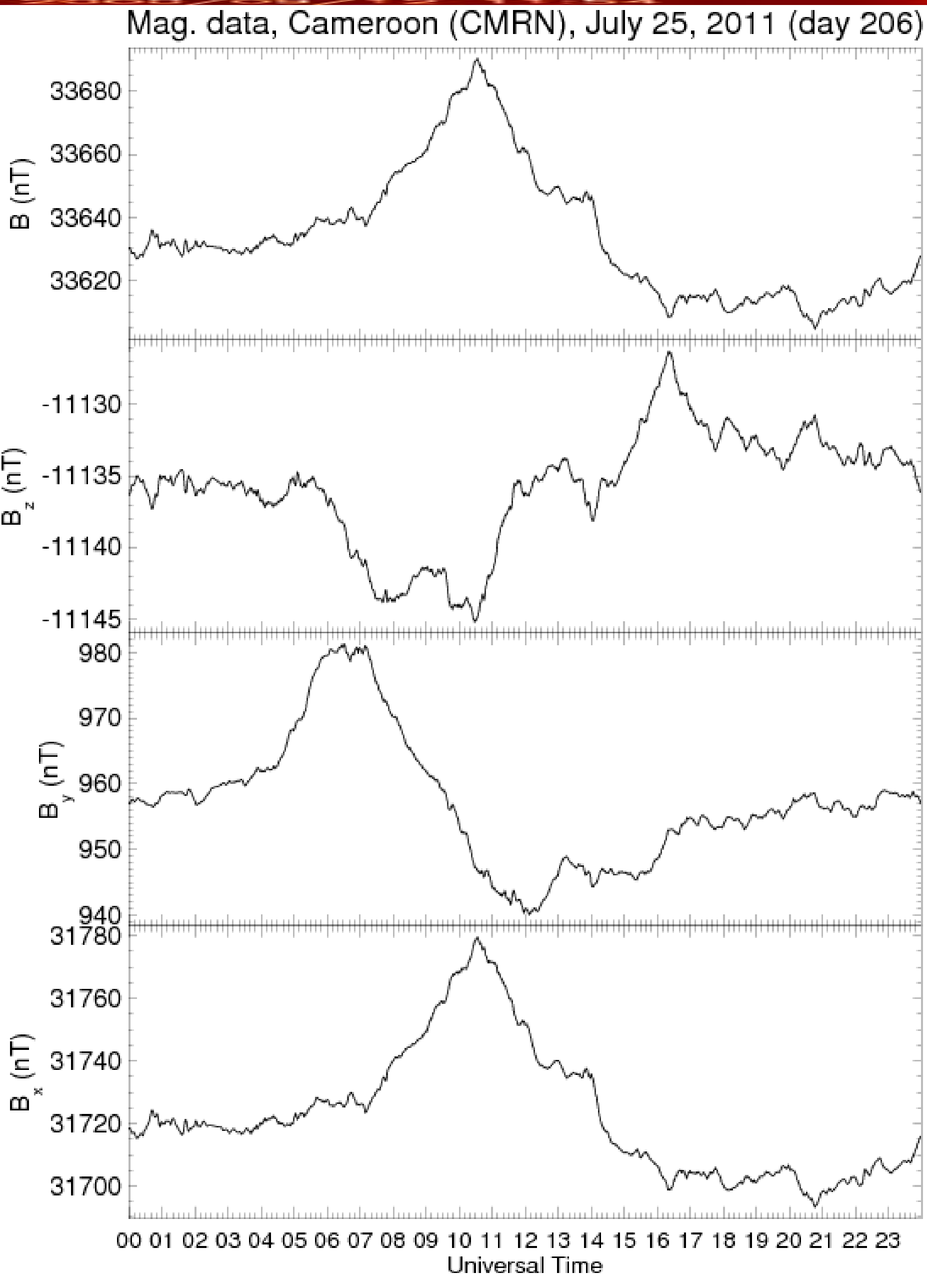
Full Setup

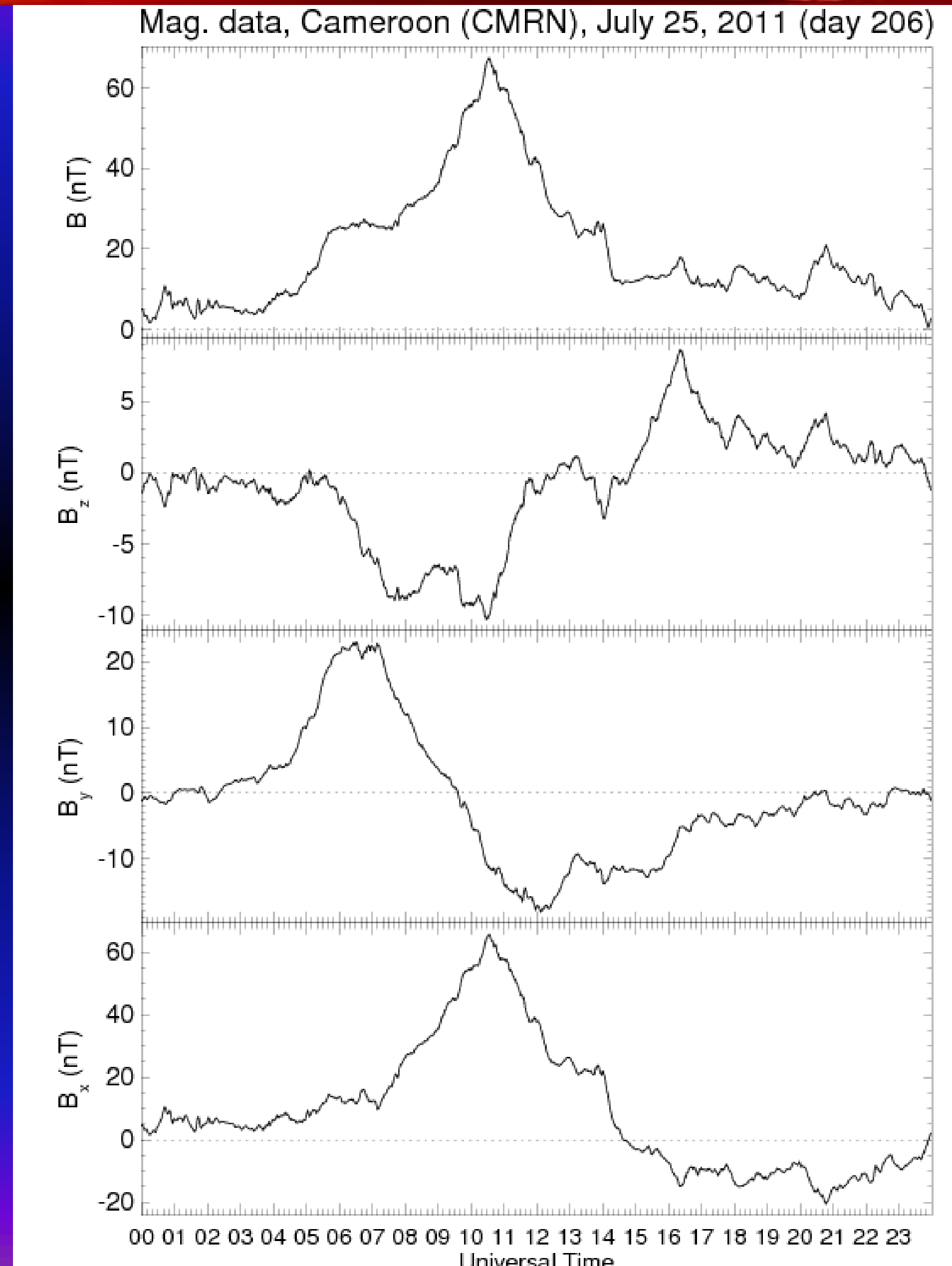


Setup at the Site

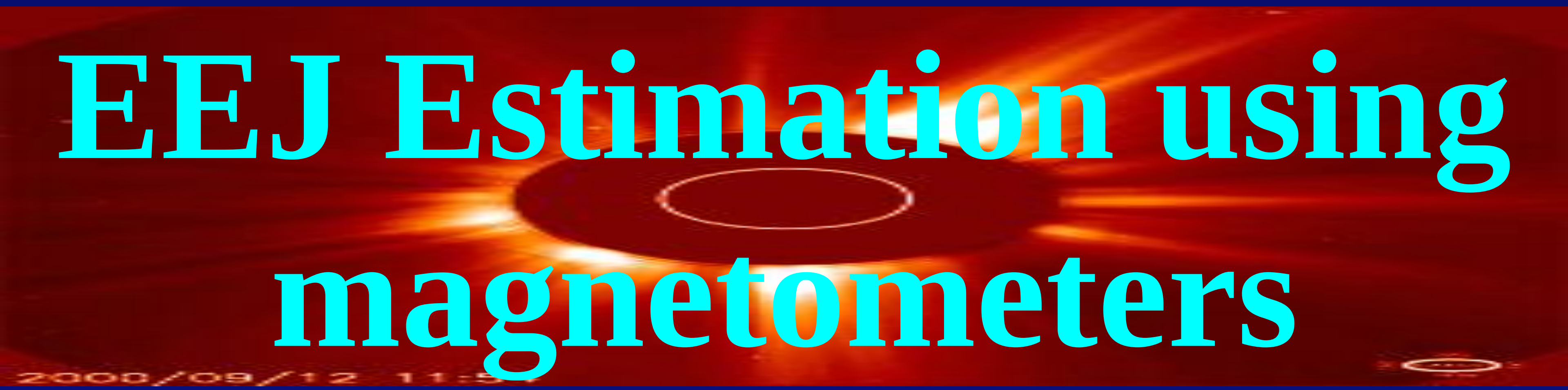
- **Sensitivity: 0.01 nT**
- **Time resolution: 0.5 sec**

What does the magnetometer Observes?

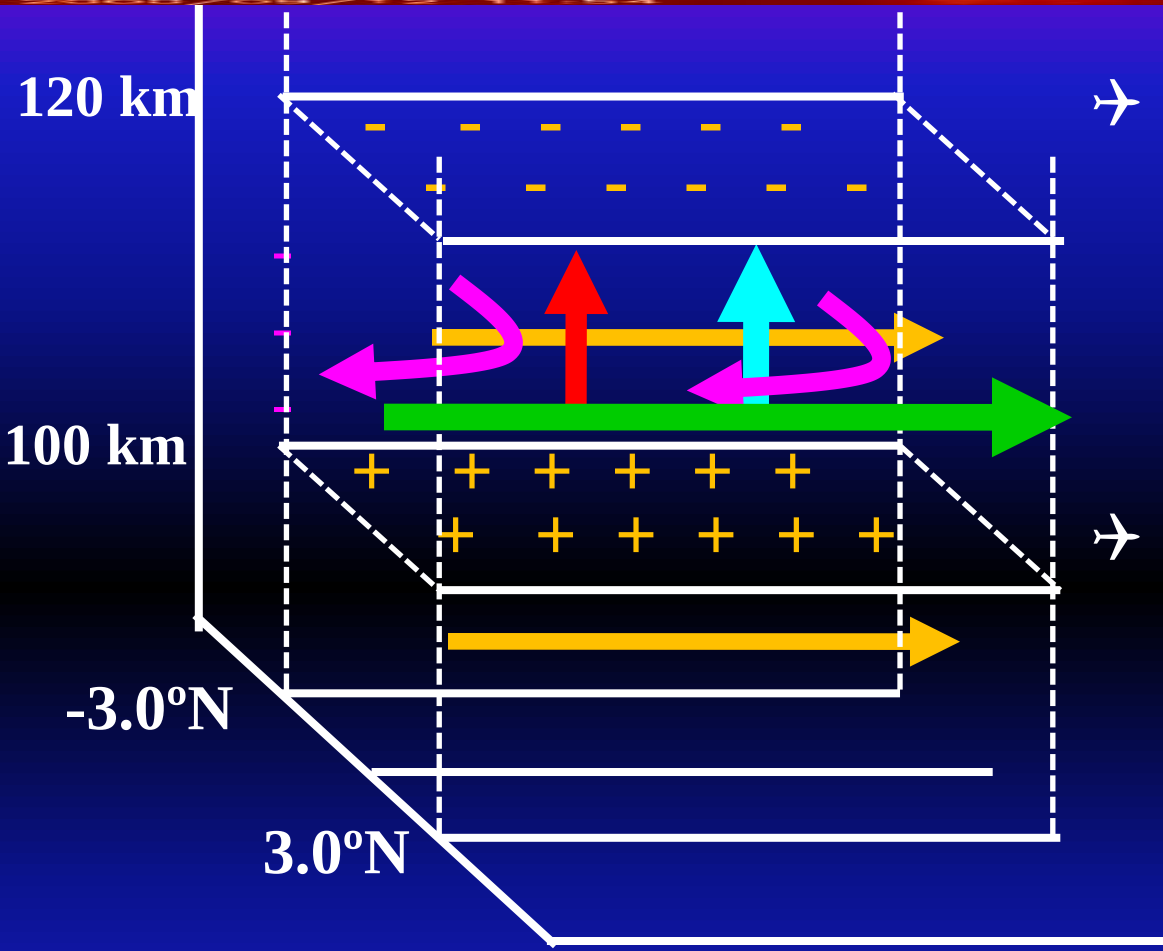




EEJ Estimation using magnetometers

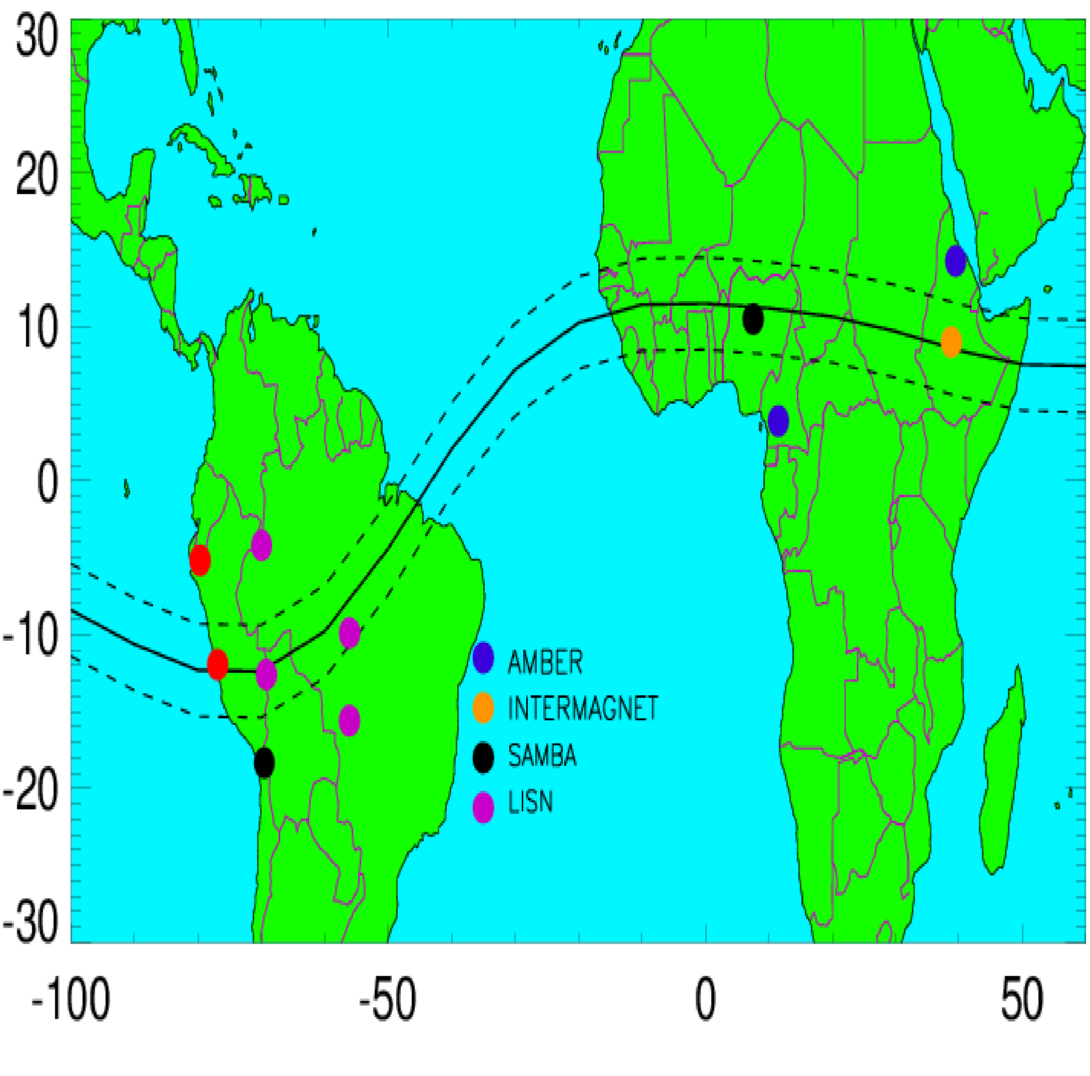


Equatorial Electrojet (EEJ) formation



- The solar-driven neutral wind results Sq current system and then east-west polarization E-field in the E-region.
- At the magnetic dip equator, the resulting upward E x B drift moves negative charge at the top and a positive at the bottom of the E-region.
- The resulting E-field prevents electrons to be drifted further upward, instead, they are propelled westward by the eastward E-field. This forms an eastward electric current flow within ±3.0º of the magnetic equator, which is called the Equatorial Electrojet (EEJ)

Then how do we measuure these EEJ currents?



- **Disturbances due to geomagnetic impact**

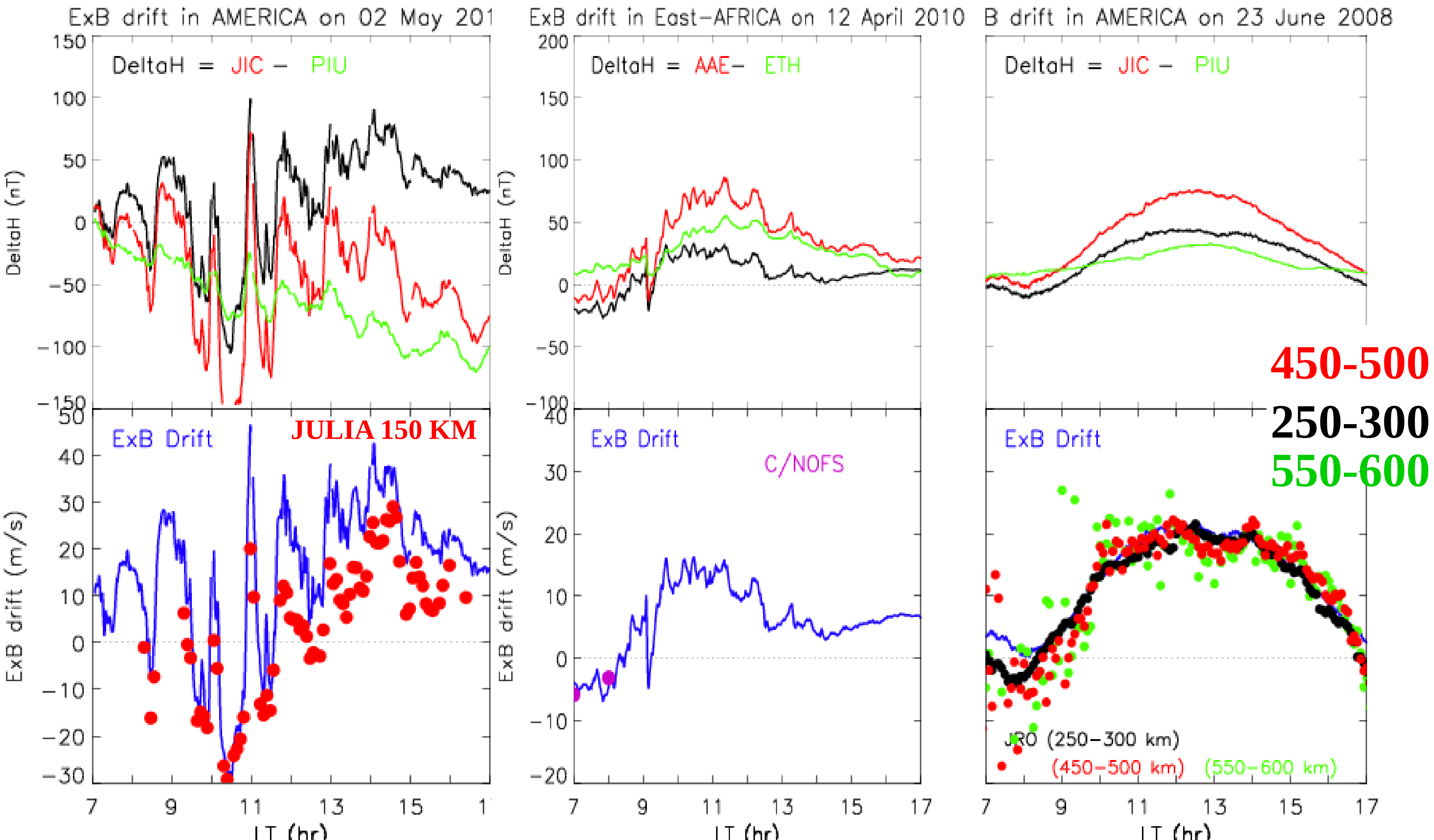
  On H-components at the equator and off the equator

- **Disturbances due to EEJ**

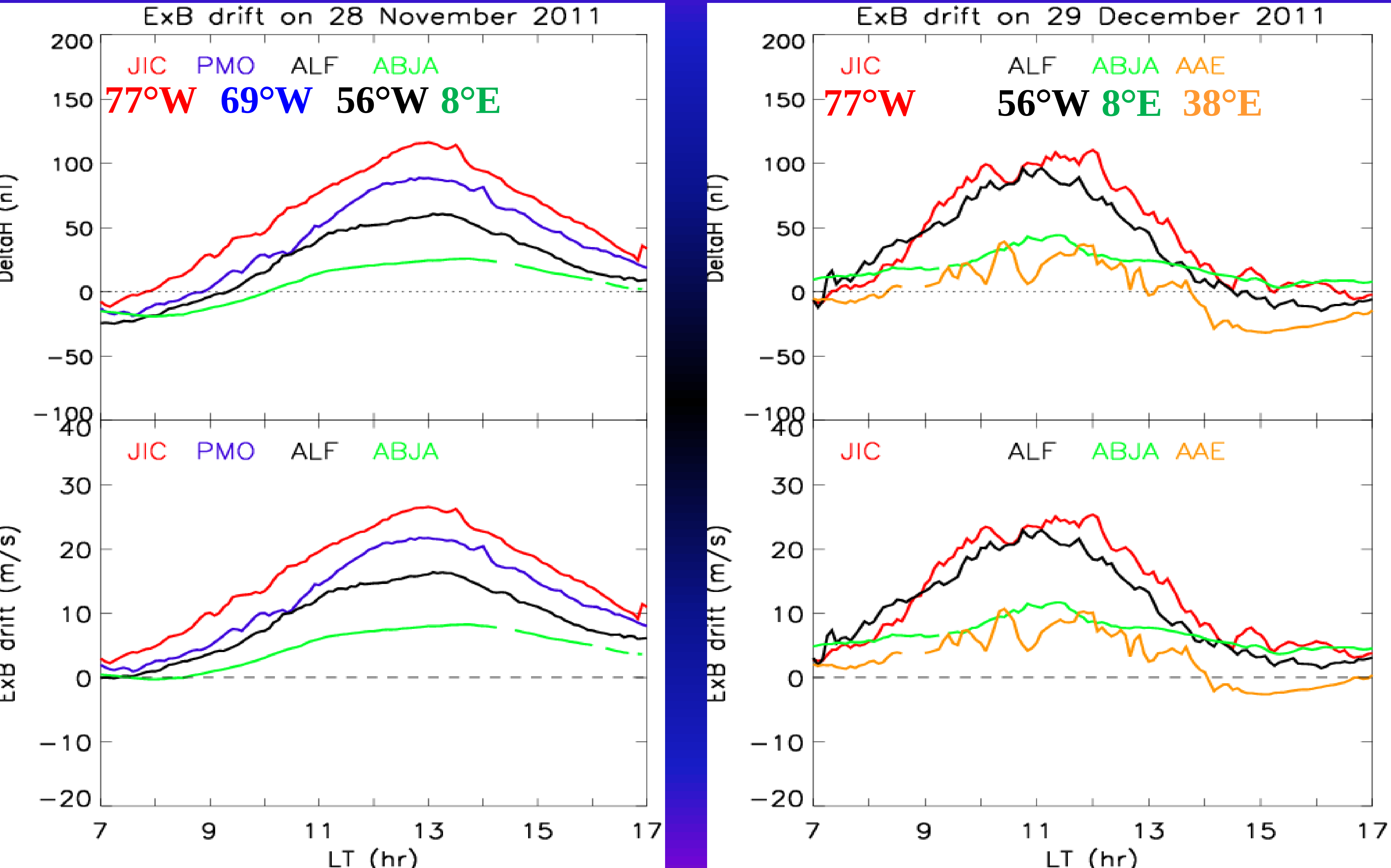
  Only on H-component at the equator

Comparison with other observations

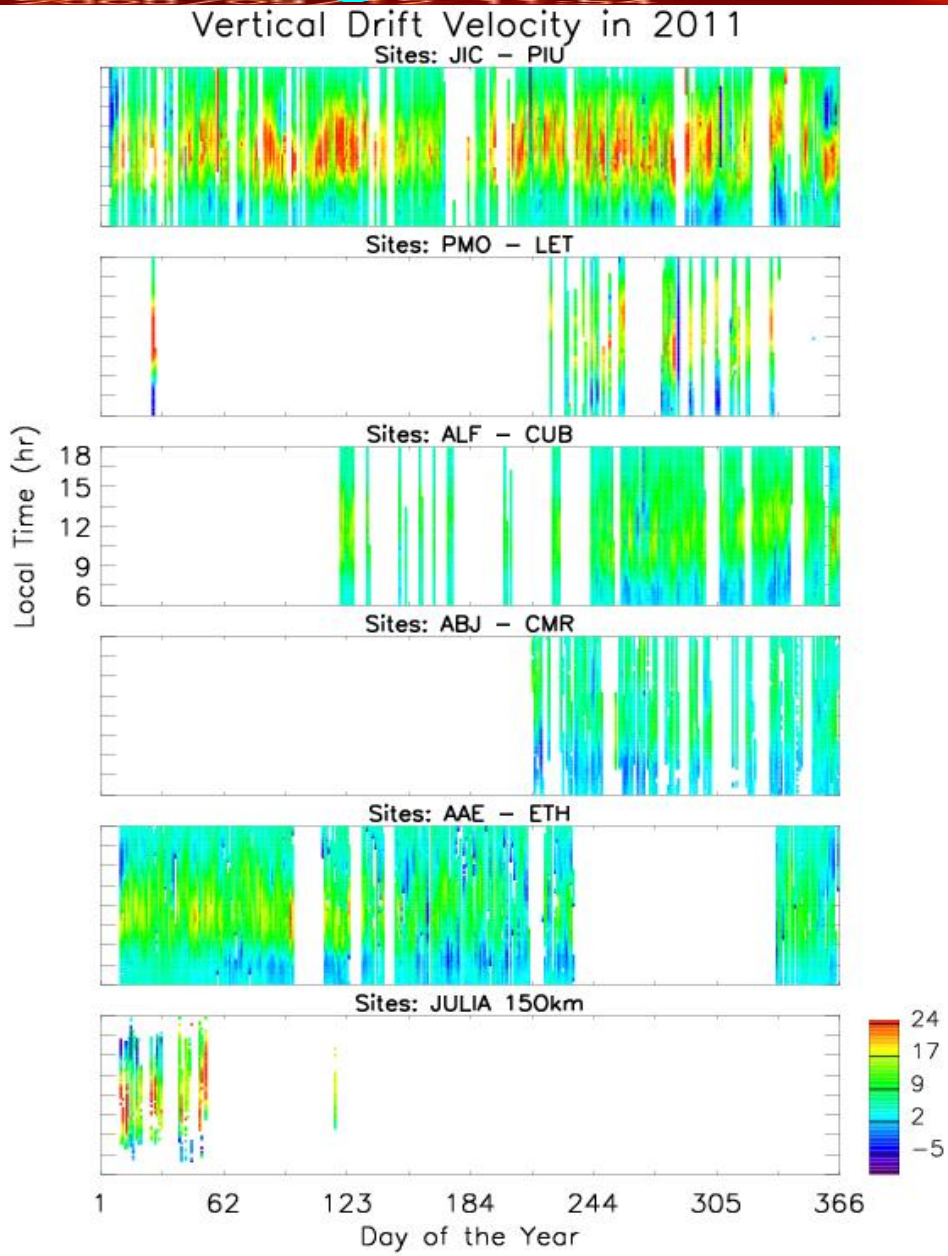
with JULIA | **C/NOFS - Africa** | **C/NOFS - America**

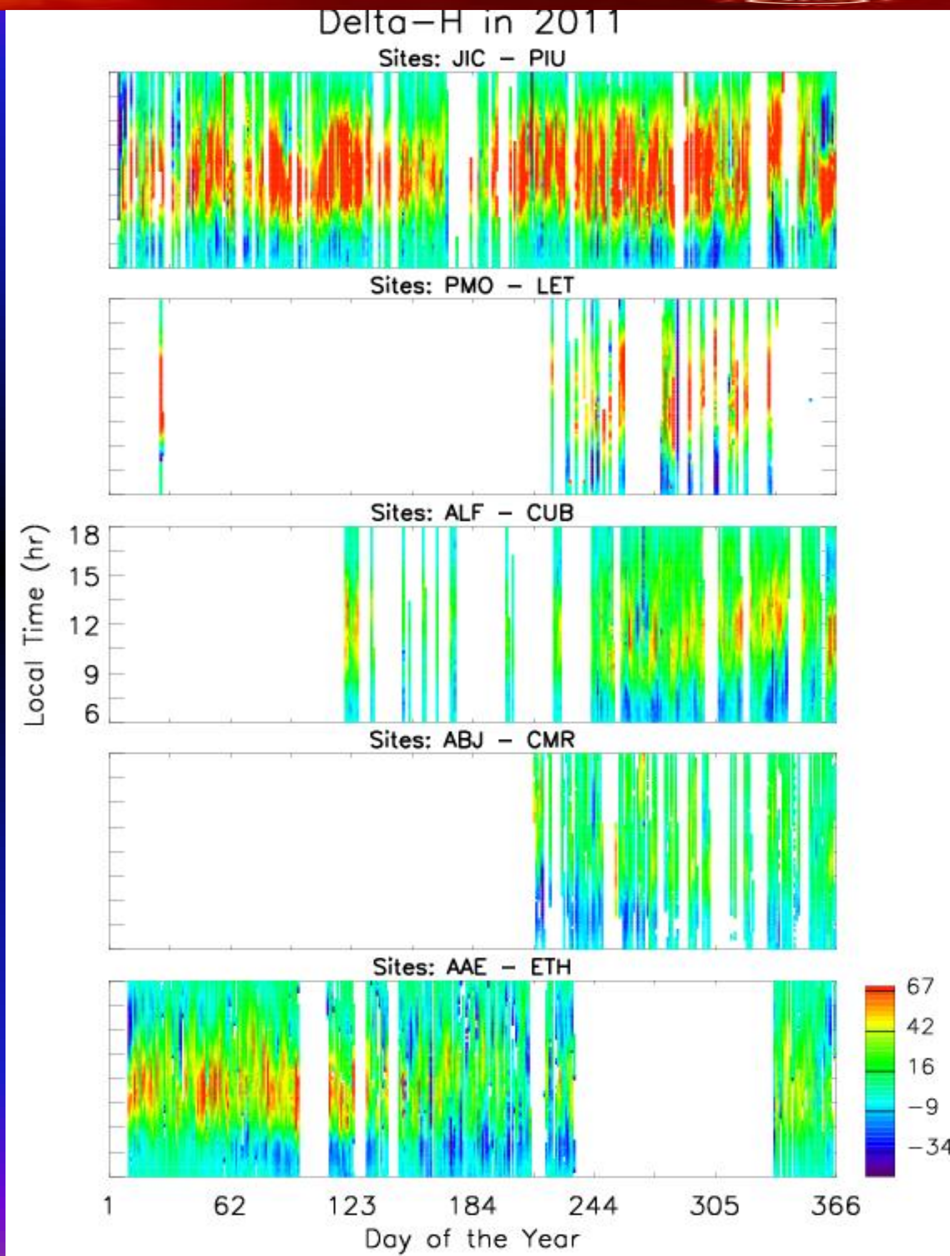


Longitudinal EEJ Variations



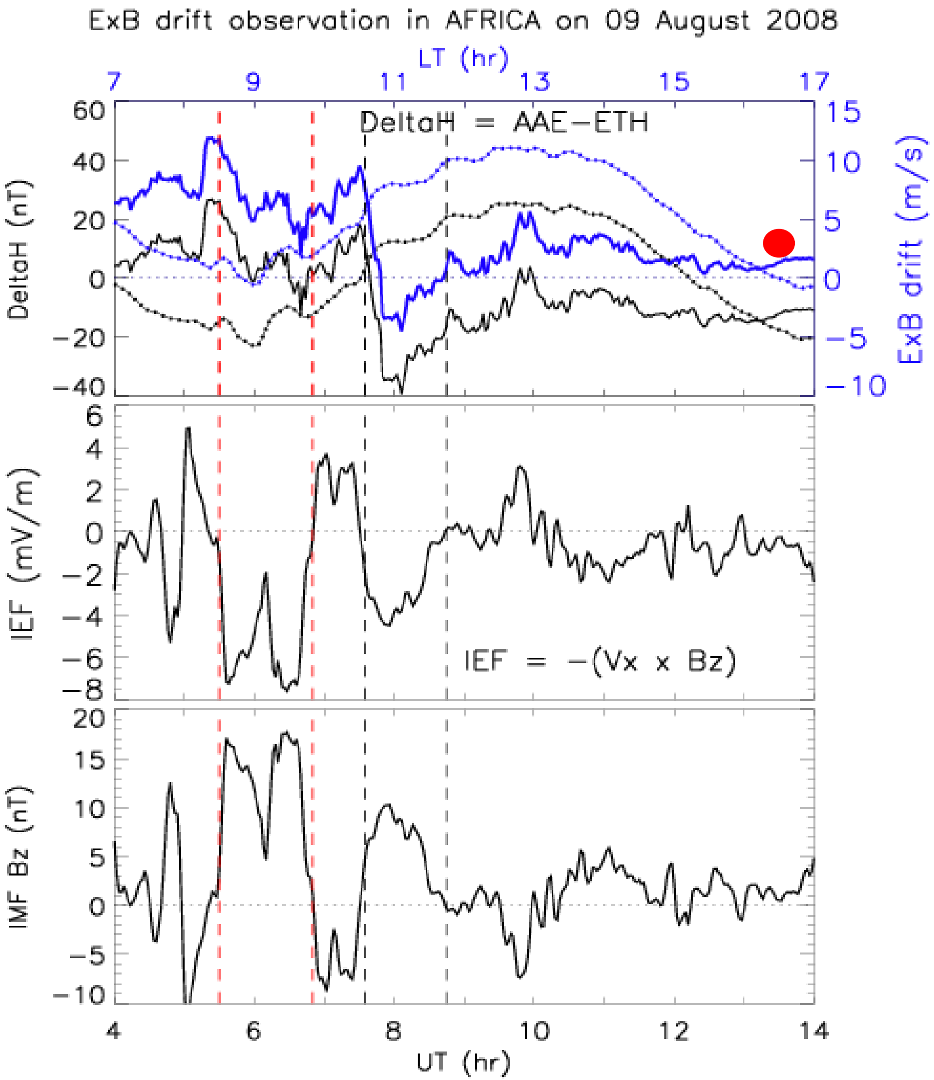
Longitudinal EEJ Variations

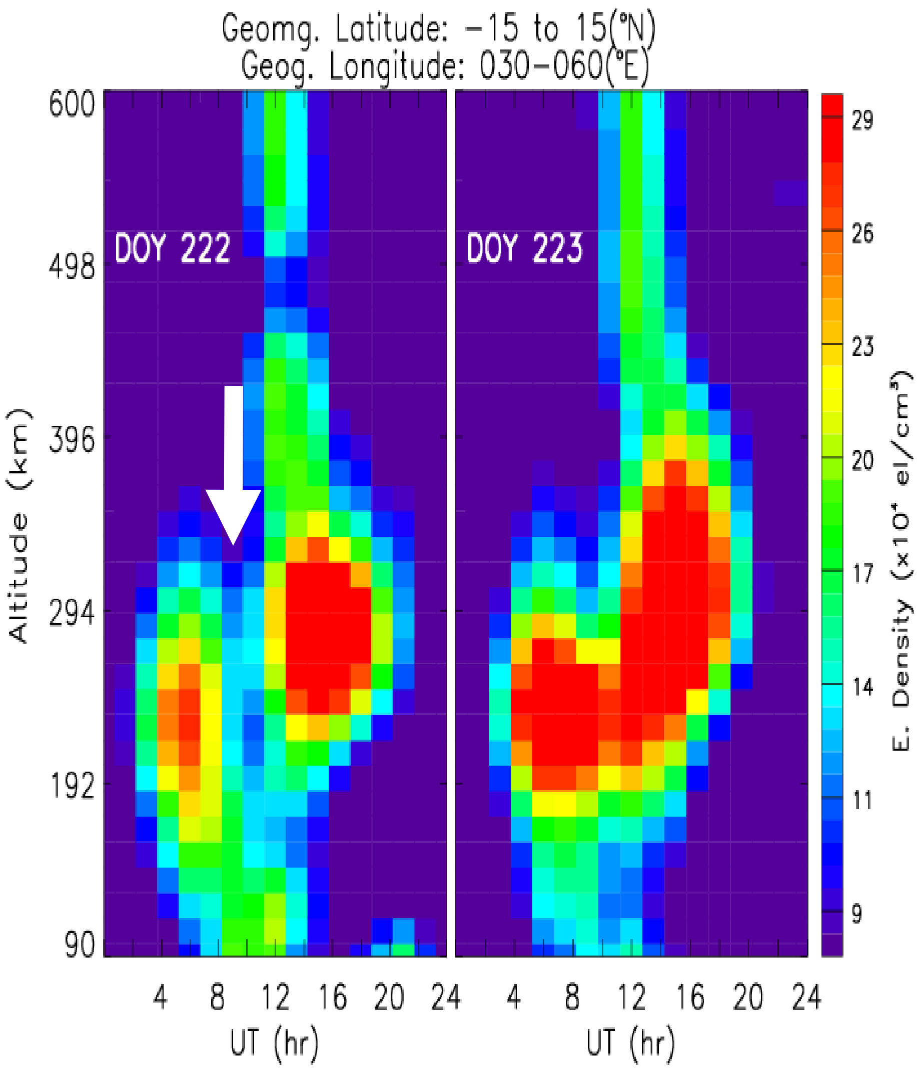




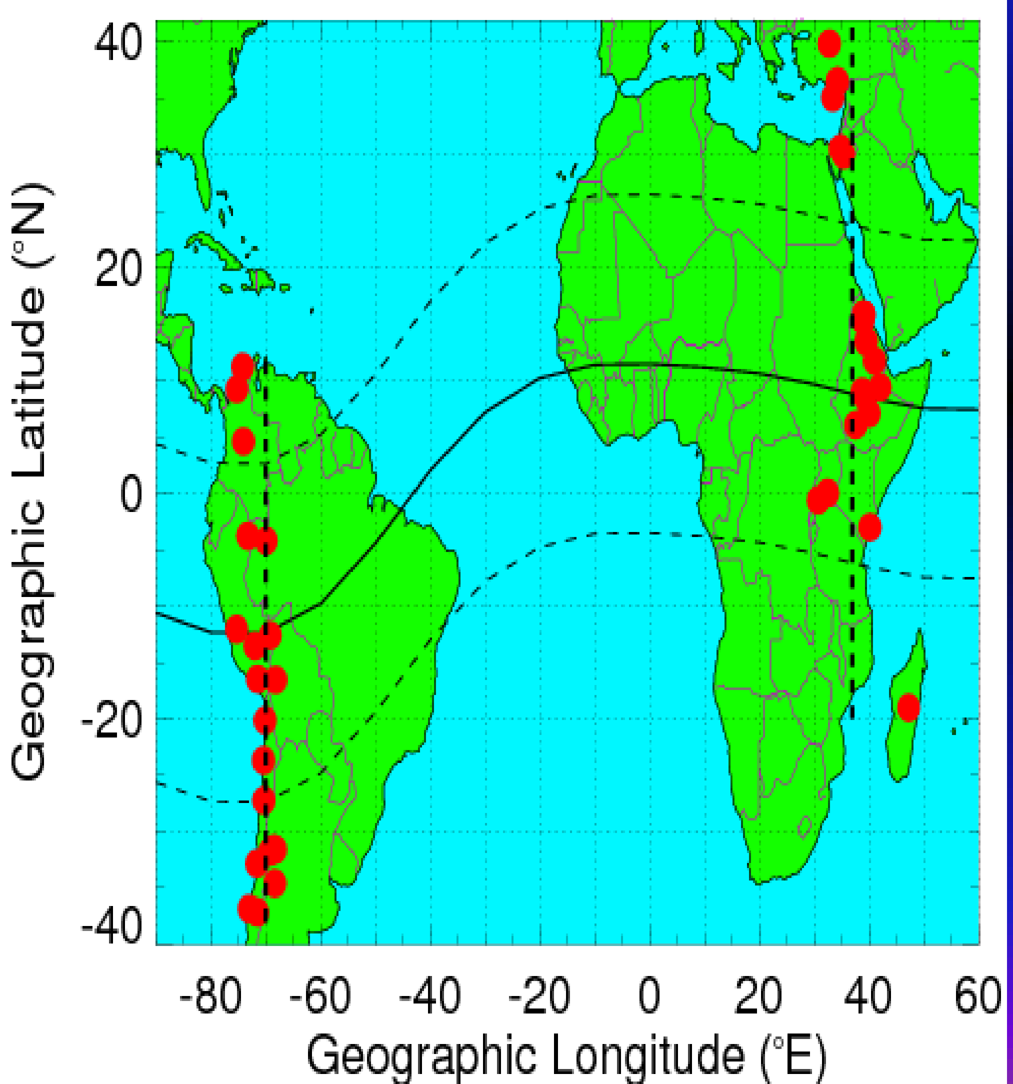
How does the ionospheric density respond to such drift differences?

Storm time electrojet and TEC & Occultation Density profile response





Computerized Ionospheric Tomography (CIT)



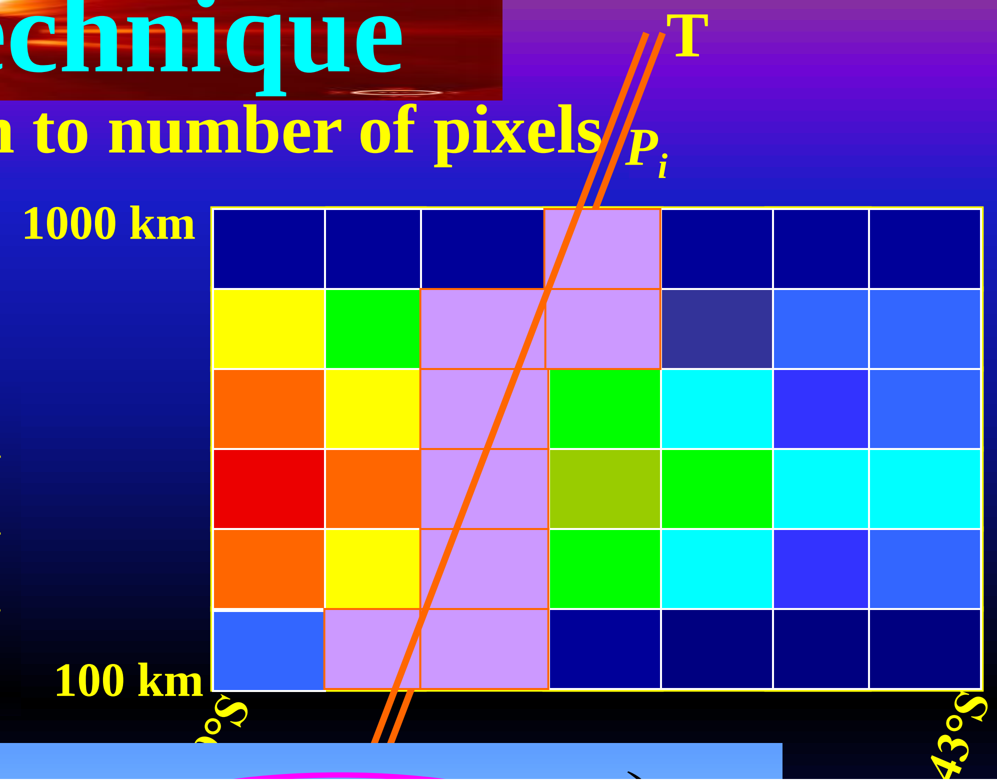
- Use radio signals from satellites
- Needs a chain of ground stations
- Use line integral of electron density (TEC) as input ingredients
- Invert data sets based on linear mathematical inversion technique
- Obtain vertical structure of electron density
- Large-scale spatial structure of ionosphere

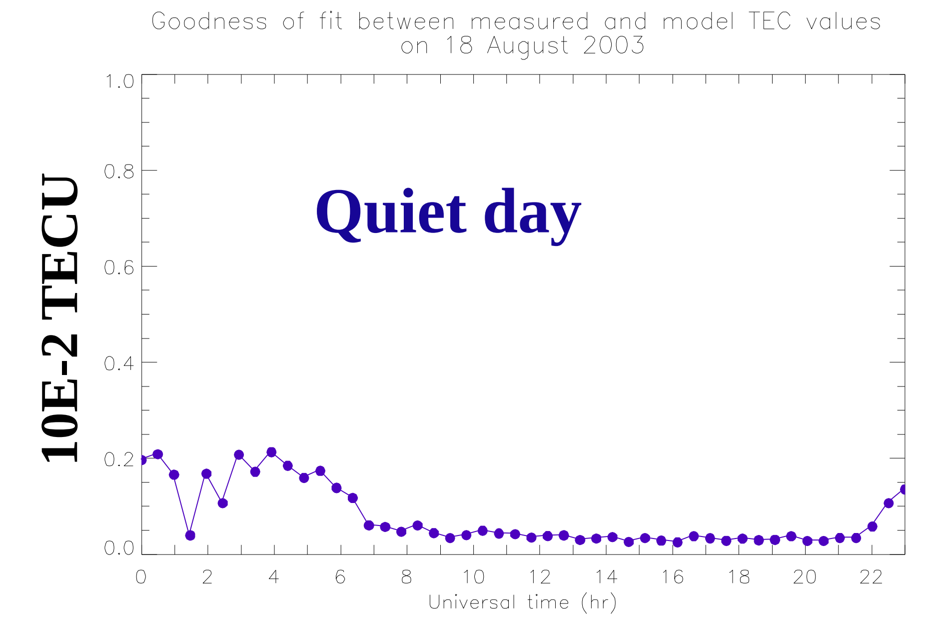
CIT Inversion technique

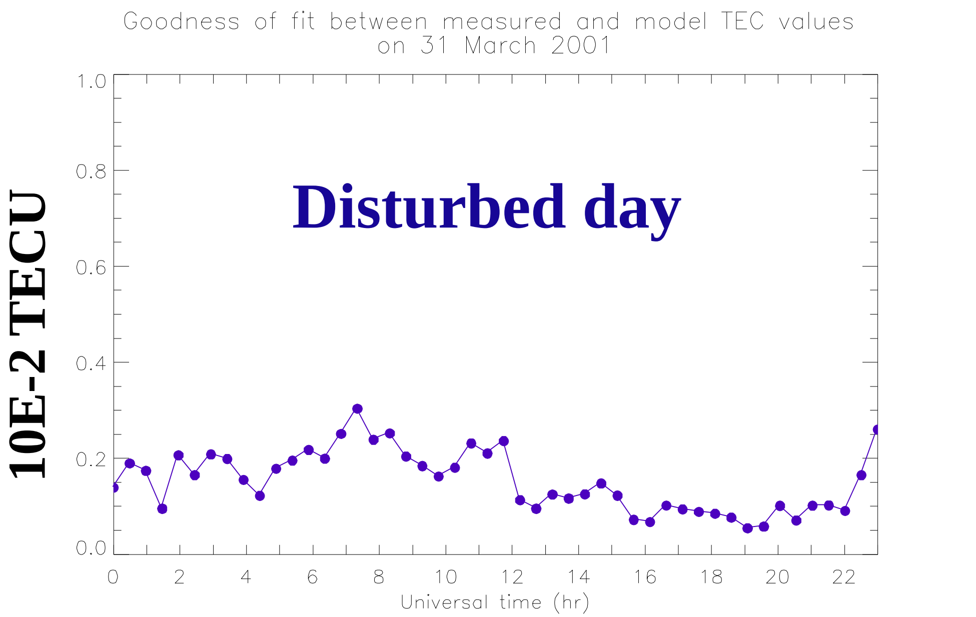
- Divide the imaging region in to number of pixels

$$TEC_i = \int_{p_i} N_e ds = \sum_{j=1}^{N} d_{ij} n_j + E$$

$$TEC_{guess} = \sum_{j=1}^{N} d_{ij} (n_{gs})_j$$

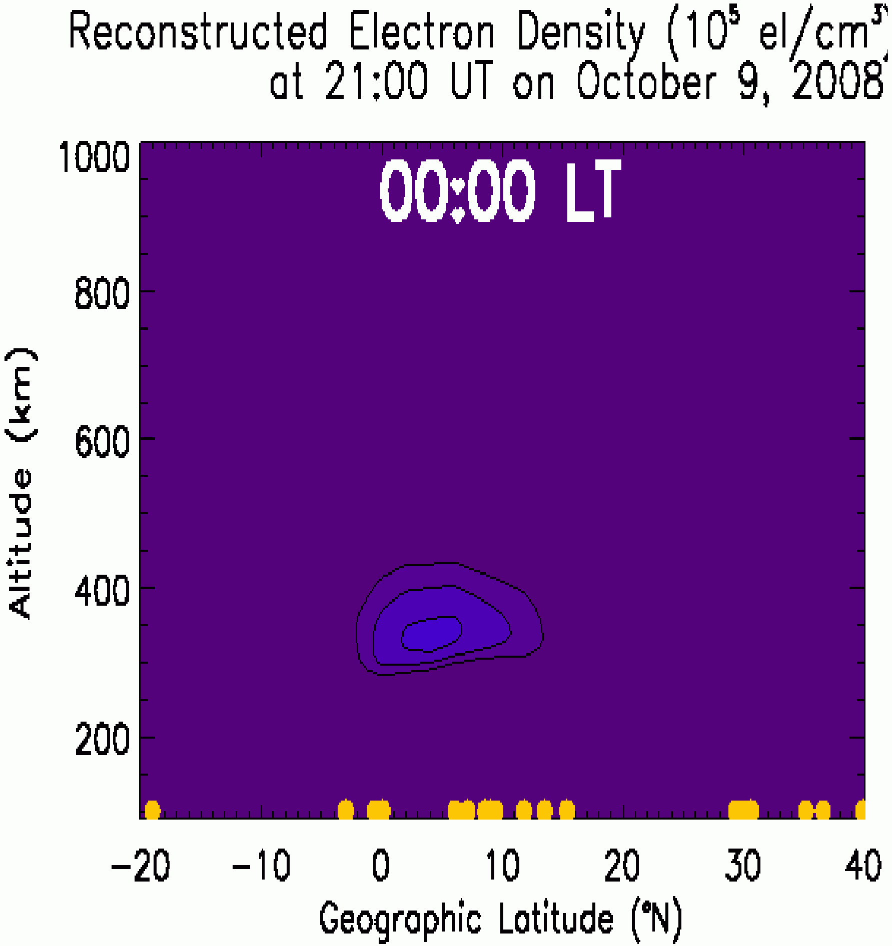


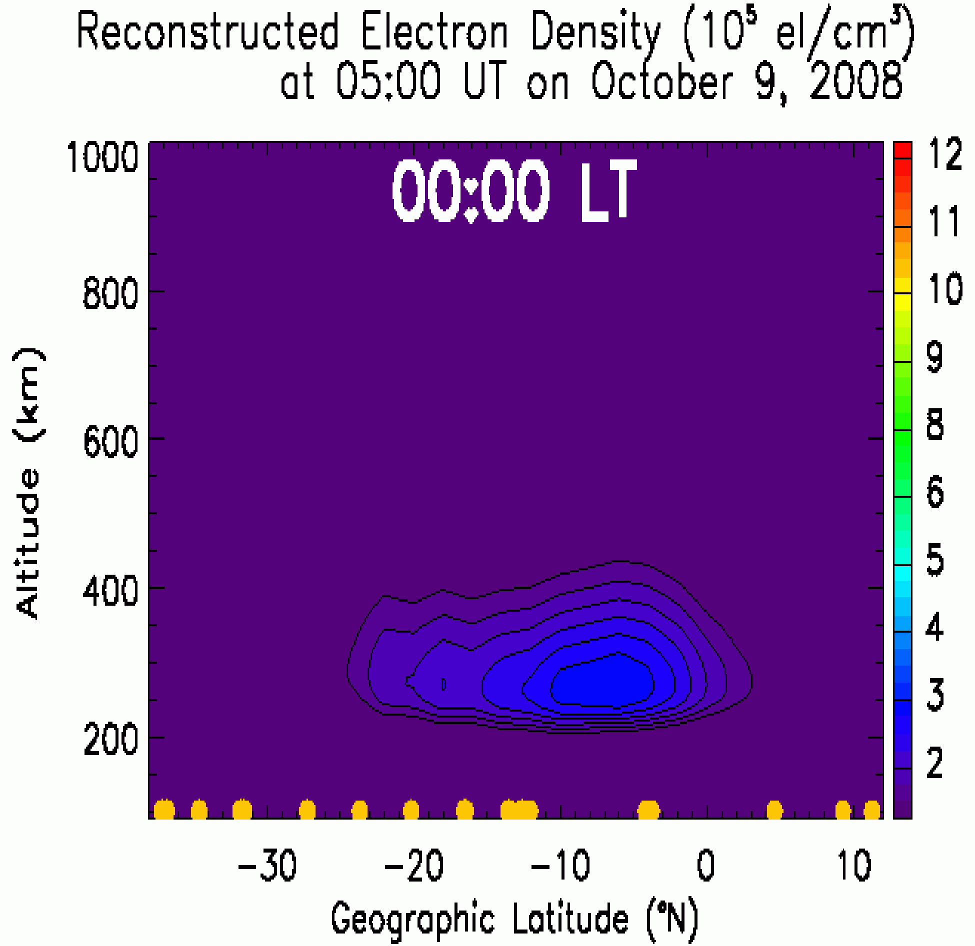




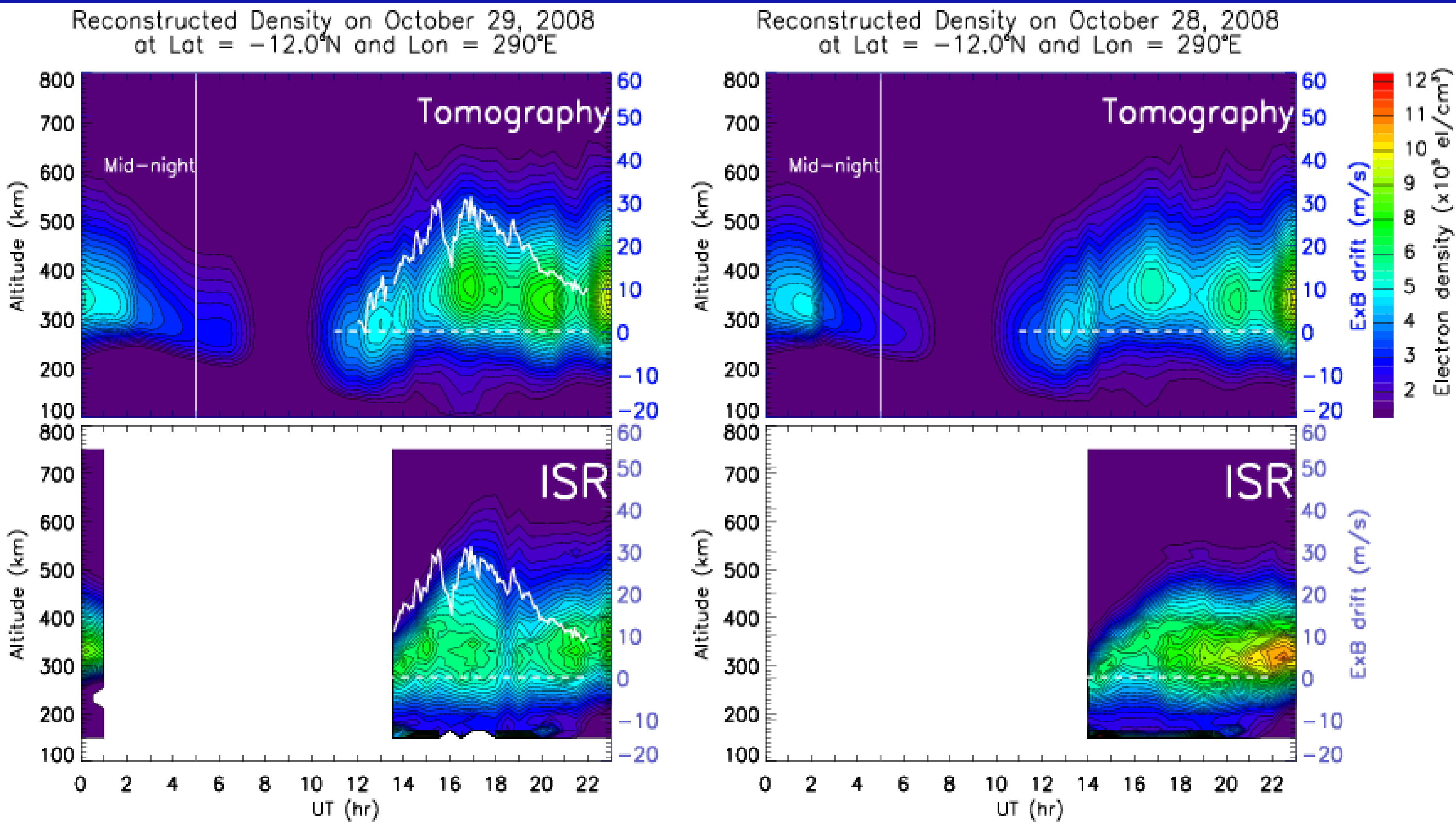
Tomographically reconstructed density profiles

East Africa — West America



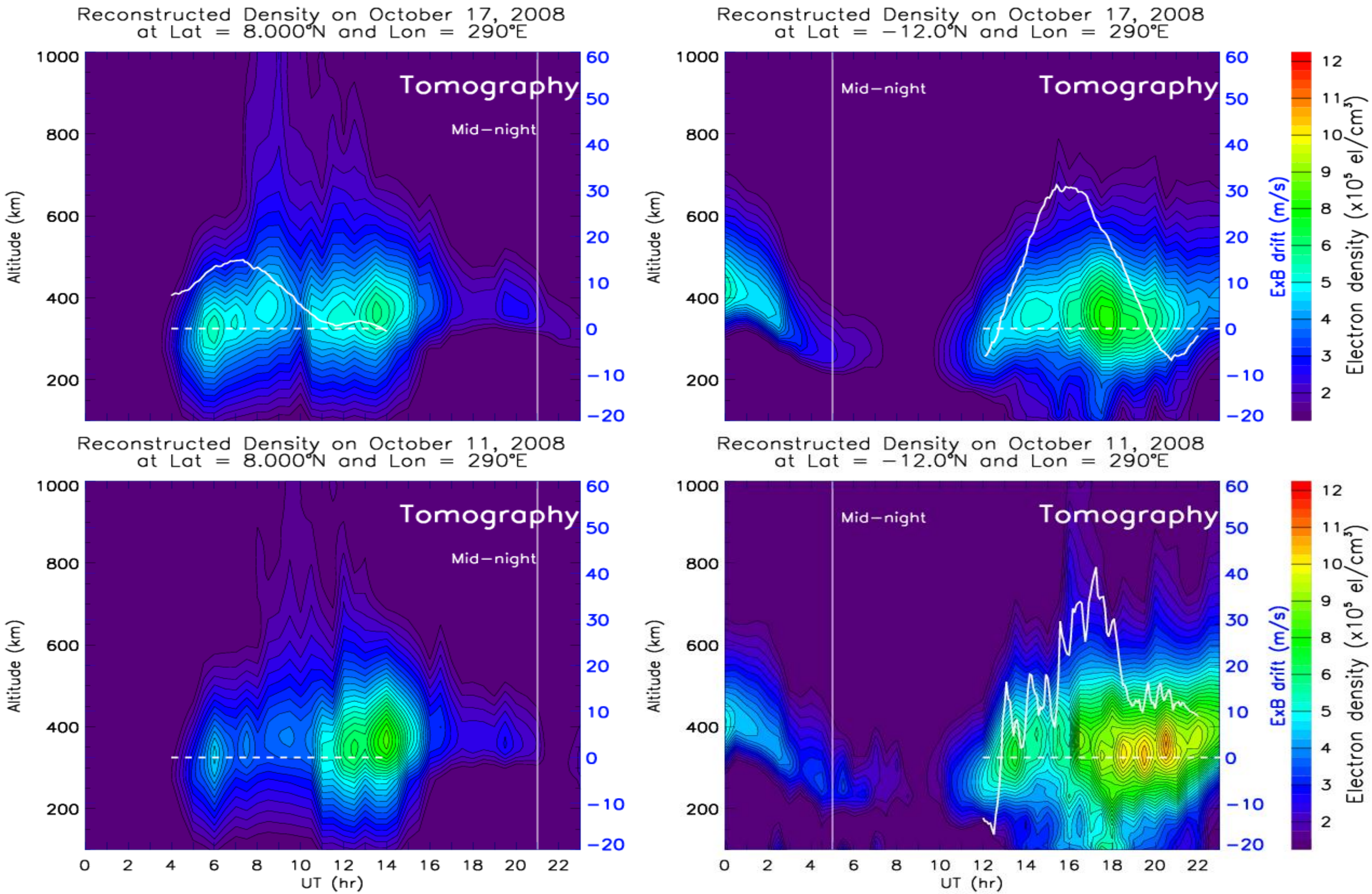


Tomography and ISR Density profiles comparison



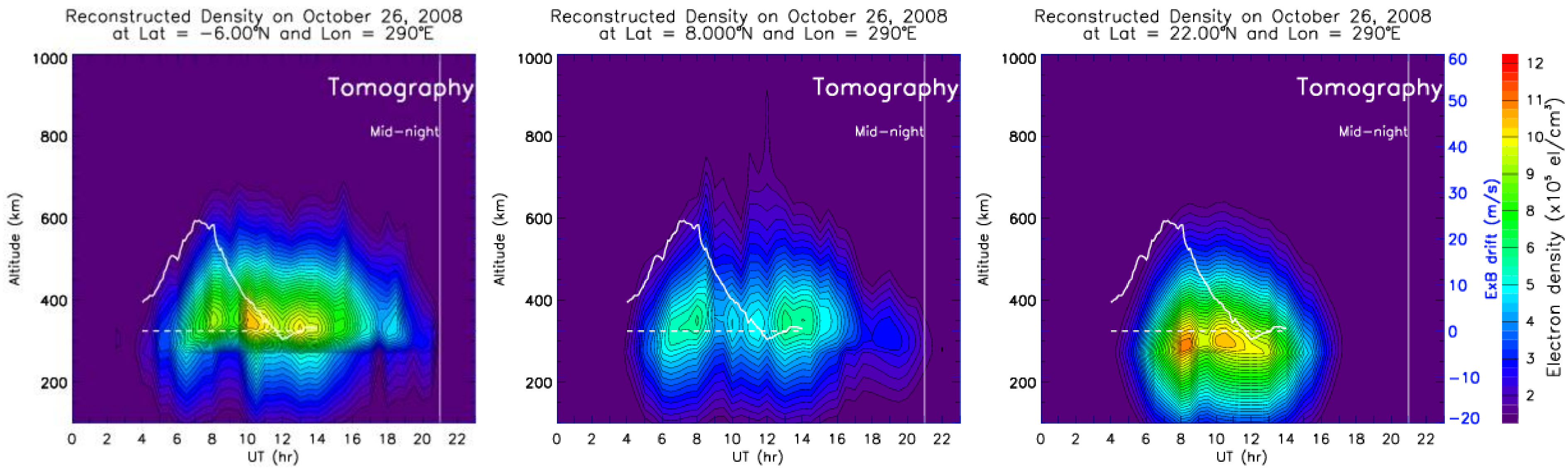
Longitudinal Density profiles differences

East Africa | **West America**

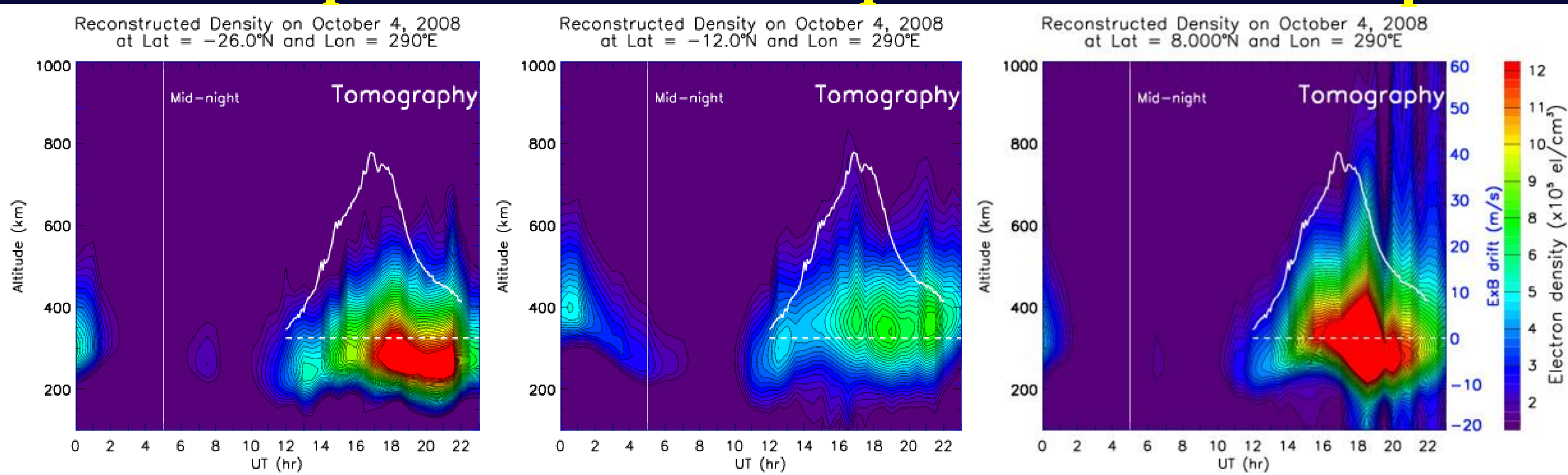


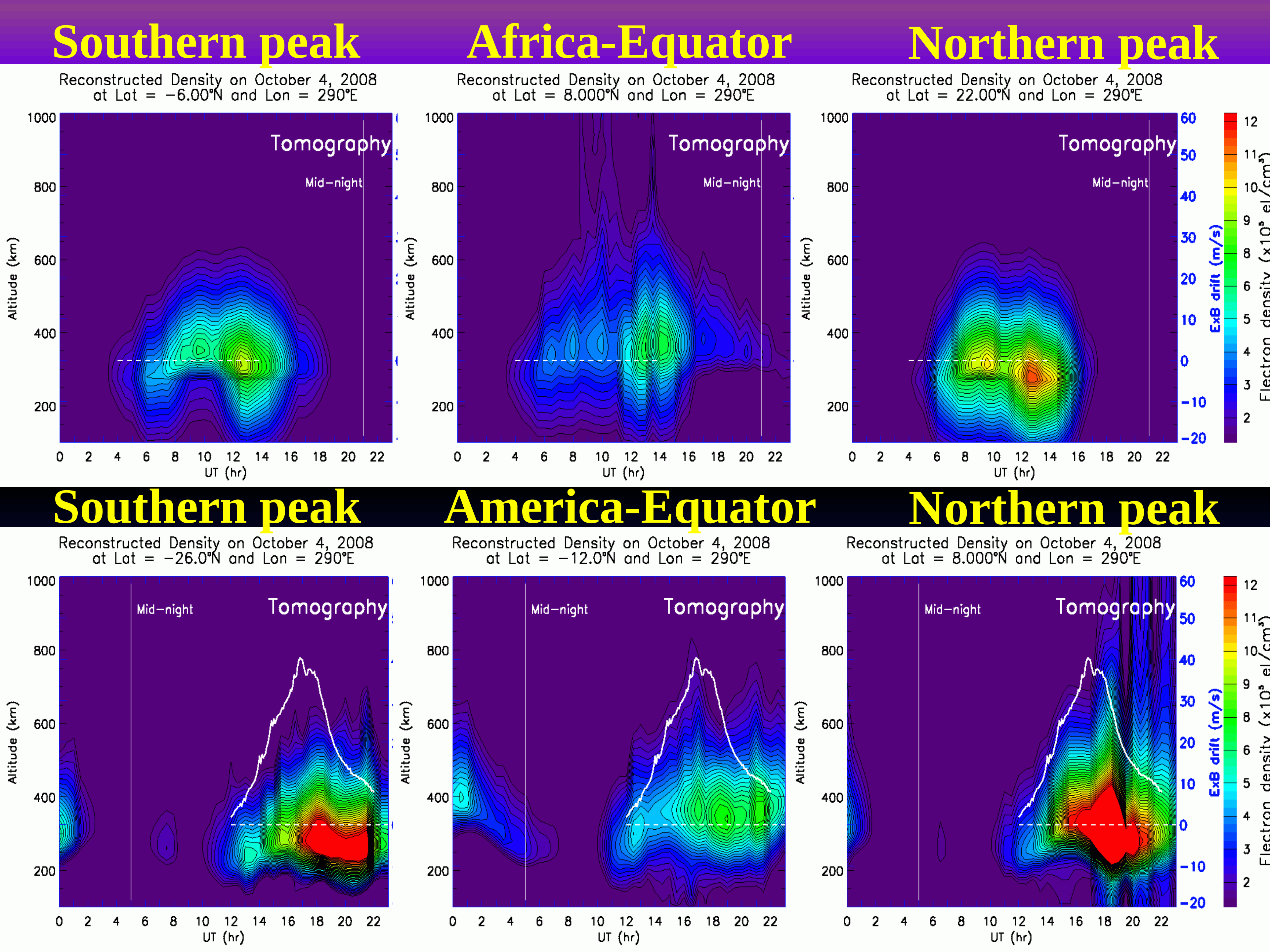
Longitudinal Density profiles differences

Southern peak　Africa-Equator　Northern peak



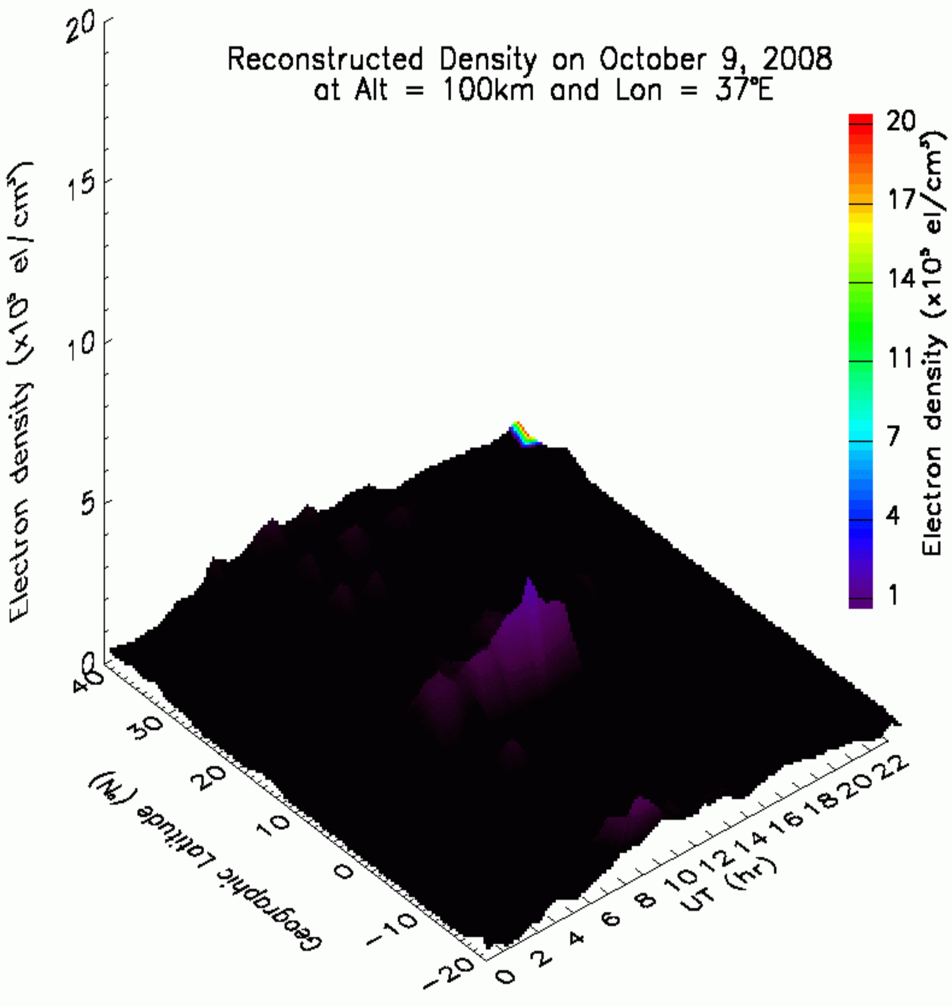
Southern peak　America-Equator　Northern peak



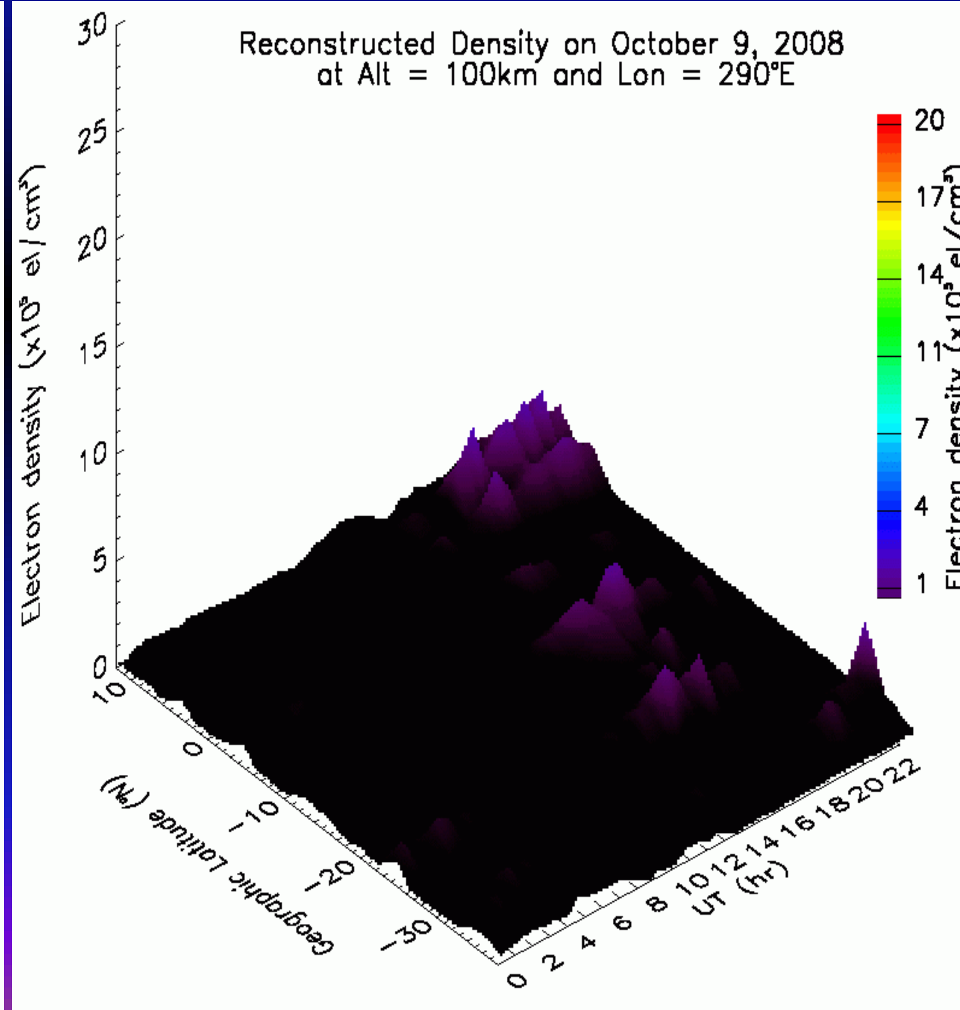

Southern peak
Africa-Equator
Northern peak
Reconstructed Density on October 4, 2008 at Lat = −6.00°N and Lon = 290°E
Reconstructed Density on October 4, 2008 at Lat = 8.000°N and Lon = 290°E
Reconstructed Density on October 4, 2008 at Lat = 22.00°N and Lon = 290°E
Tomography
Mid−night
Altitude (km)
UT (hr)
ExB drift (m/s)
Electron density (x10⁵ el/cm³)
Southern peak
America-Equator
Northern peak
Reconstructed Density on October 4, 2008 at Lat = −26.0°N and Lon = 290°E
Reconstructed Density on October 4, 2008 at Lat = −12.0°N and Lon = 290°E
Reconstructed Density on October 4, 2008 at Lat = 8.000°N and Lon = 290°E

Electron Density structure at different altitudes

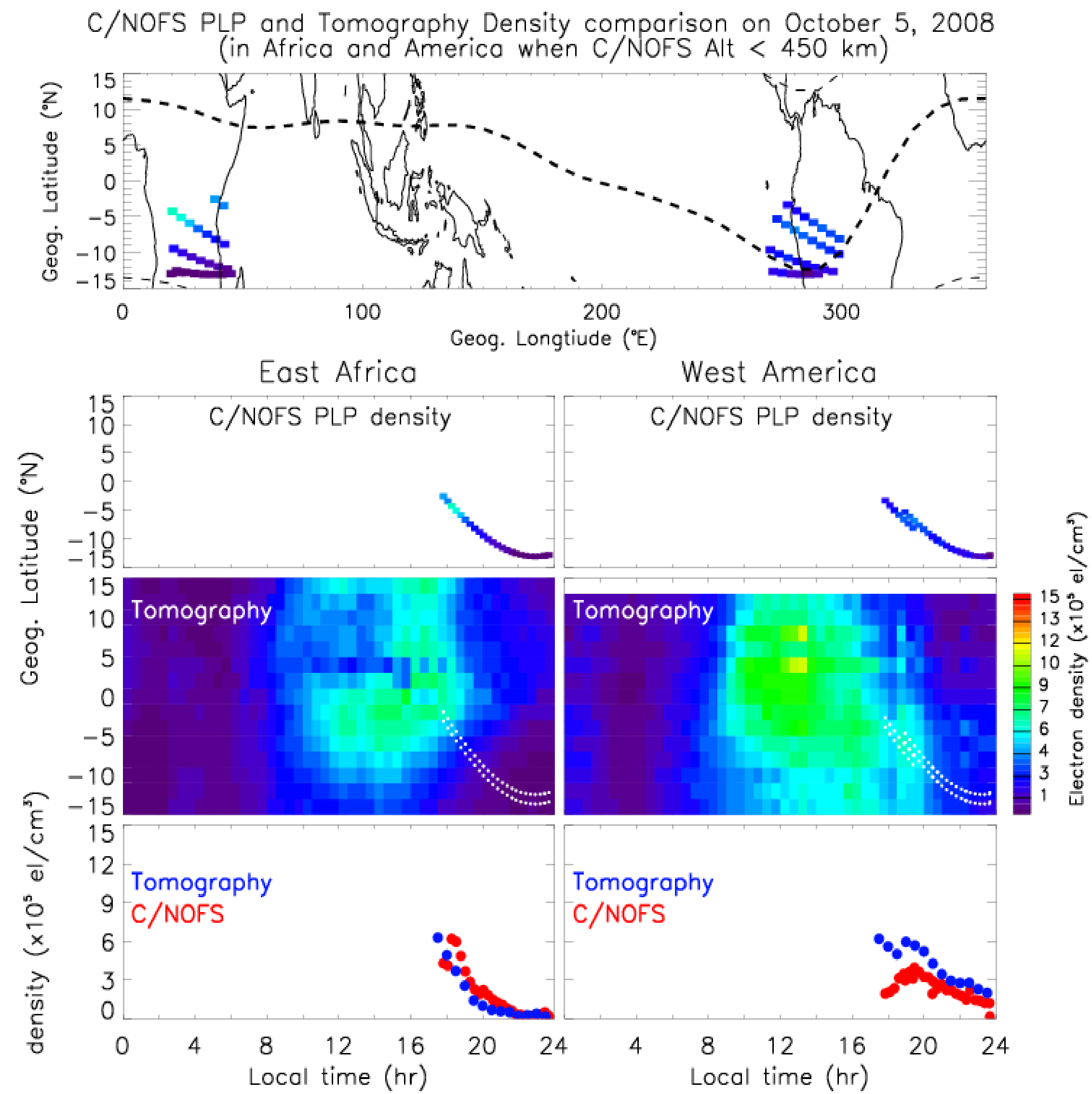
East Africa



West America



CNOF/S PLP and tomography density comparison



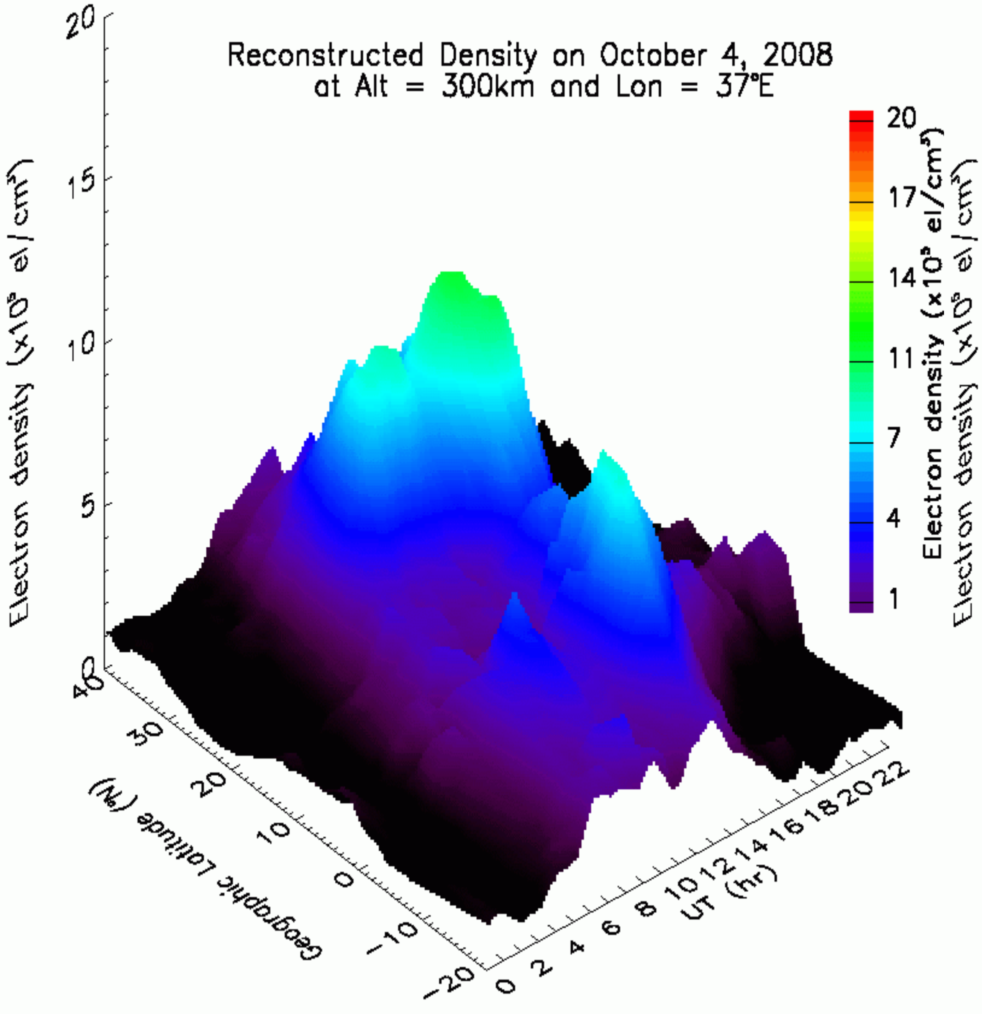
C/NOFS density distribution on October 5, 2008

Local-time distribution of C/NOFS density

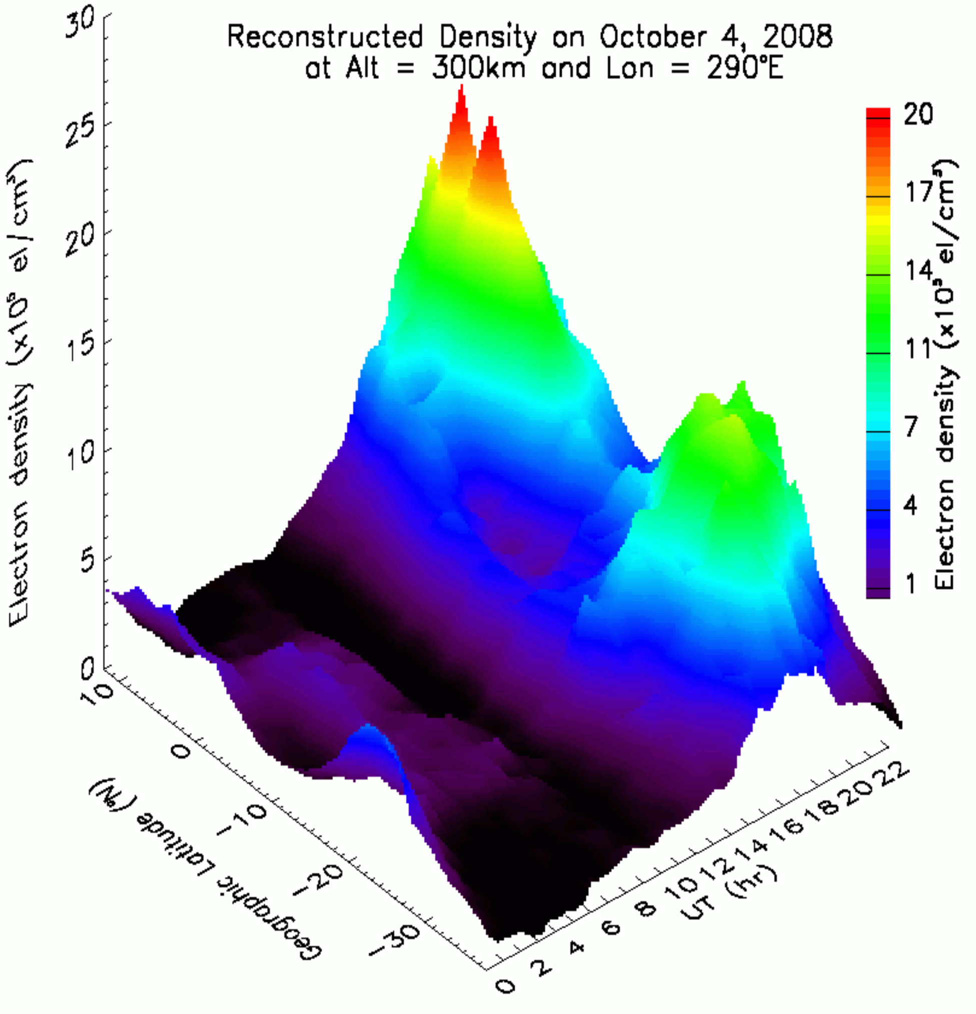
Tomography density at 420 km

F-region (at 300km) Electron Density day-to-day variability

East Africa



West America



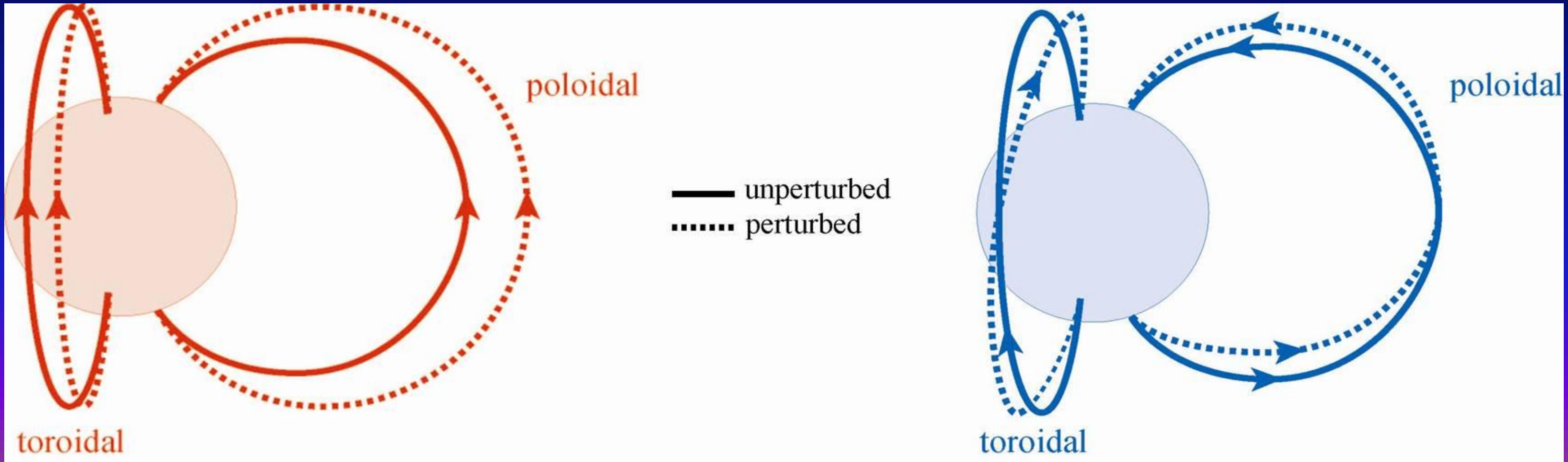
Conclusion

- The magnitude and direction of the vertical drift shows significant difference at different longitudinal sectors.
- Magnetometer is very cheap and very reliable instrument to estimate the dayside vertical drift, which the prominent parameter that governs the equatorial electrodynamics.
- The ionospheric density also responded differently at different longitudinal sectors, lower density in the east African sector than west American sector.
- The tomographically inverted density is important to monitor the day-to-day variability of the density at different altitudes, as well as for validation of the in-situ density observations onboard LEO satellites.

SCINDA talk will follow

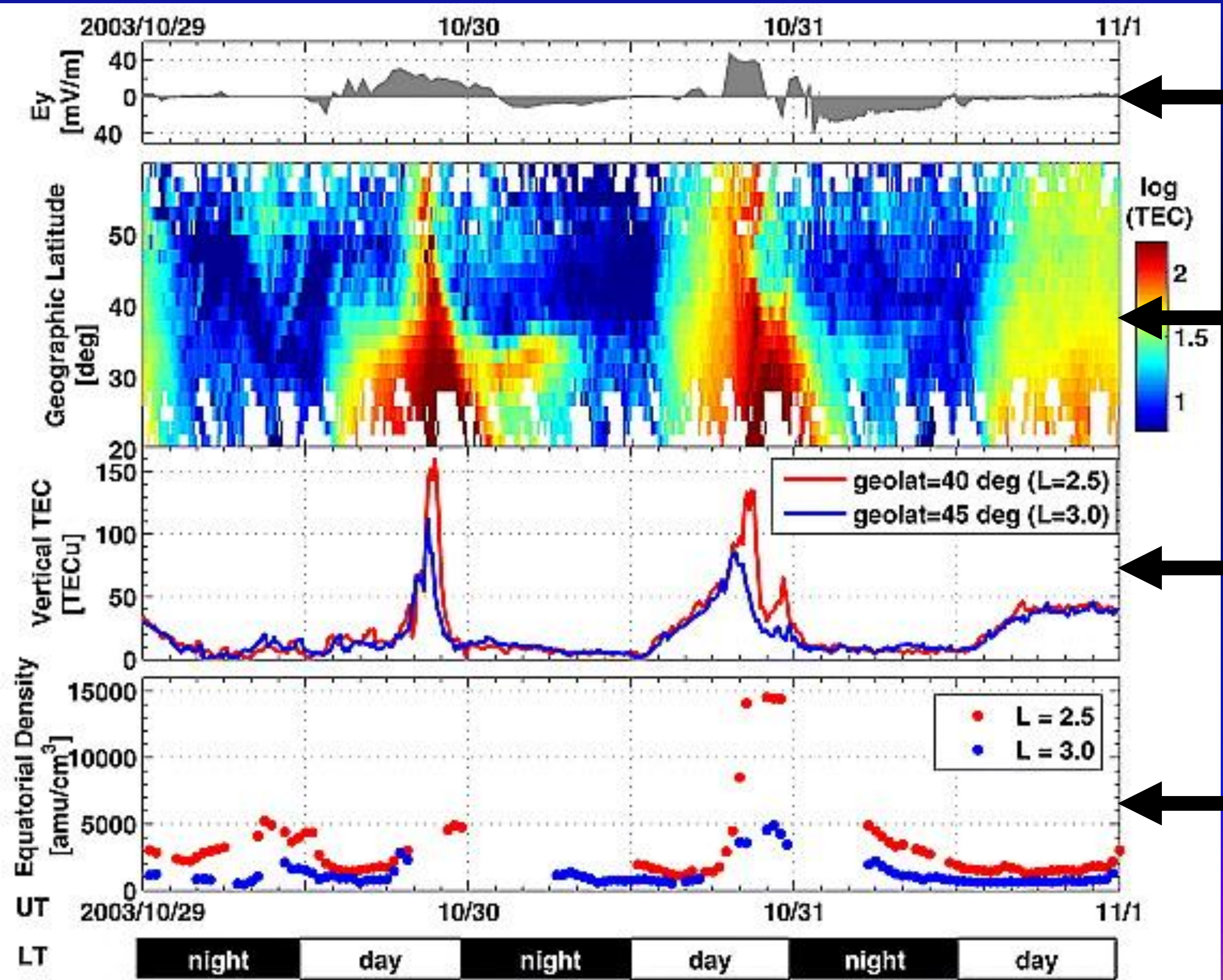
ULF or Alfven Waves and mass density

- Frequency is function of field line length (string length), field strength (string tension), and mass density of plasma (mass of string)
- $V_A = B/(\mu_o \rho)^{1/2}$
- Field-line standing wave period
  - $T = (2/n) \int ds/V_A$ [Dungey, 1954]



Simultaneous density enhancement in the plasmasphere and ionosphere

Chi et al., GRL, 2005



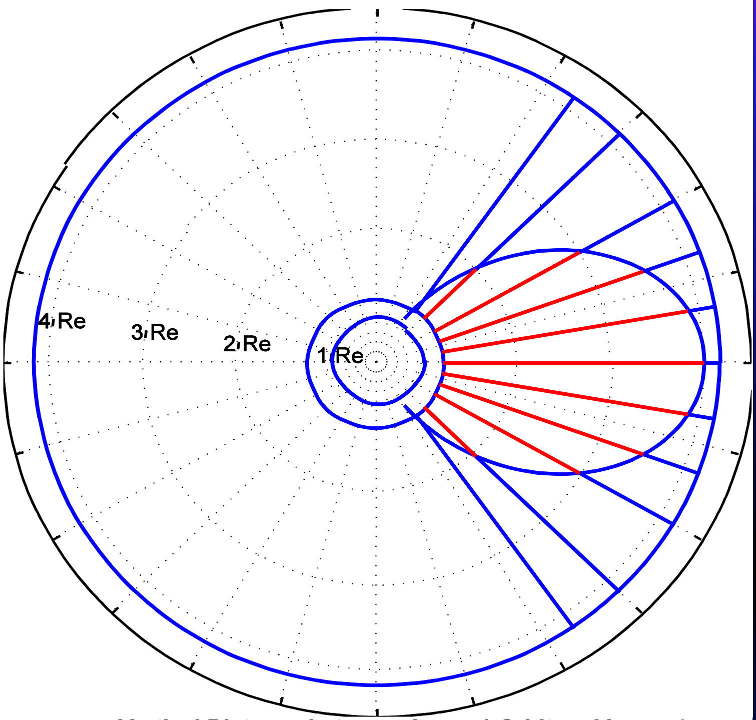
East-west electric field ($E_y = V_x \times B_z$)

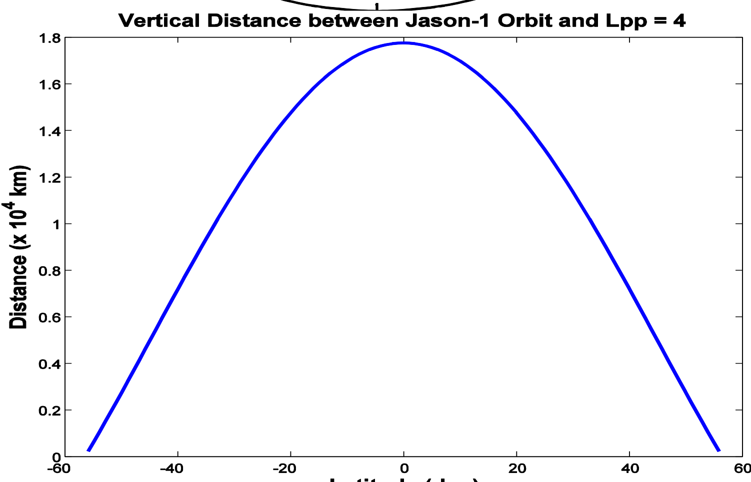
The vertical total electron content (TEC) along 255°E geographic longitude

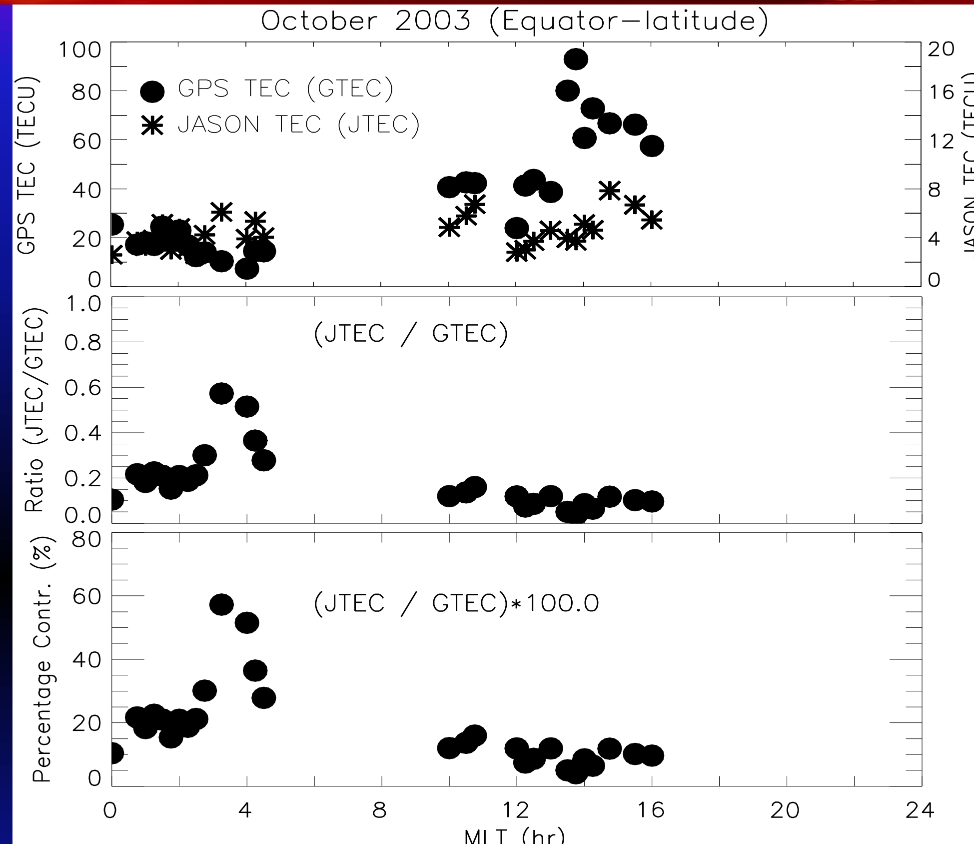
The vertical TEC values at *L* = 2.5 and 3.0

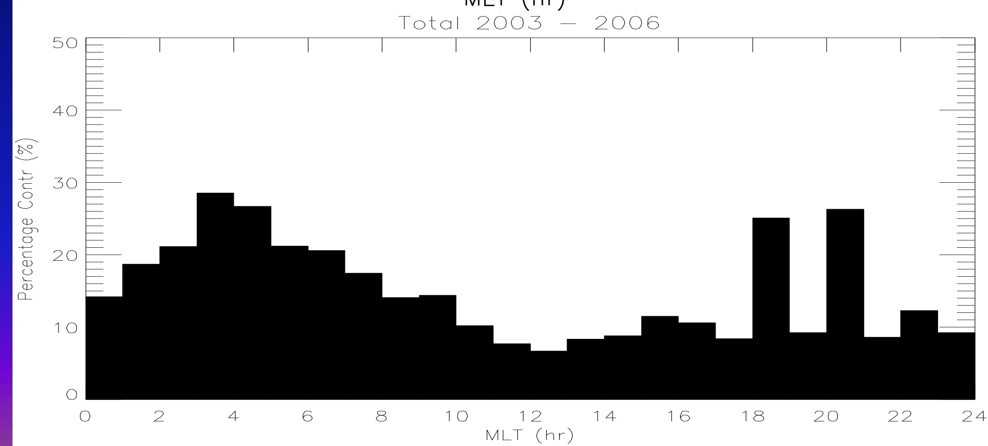
Mass density inferred by field line resonance measurements

How much the plasmasphere contribute?









Yizengaw et al., JASTP, 2008