Five years of C/NOFS Observations: Equatorial Space Weather

Space Weather Workshop, 2013

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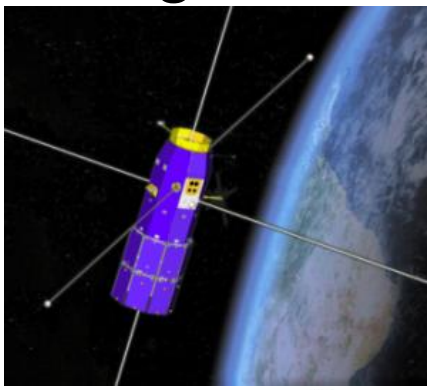
Integrity ★ Service ★ Excellence

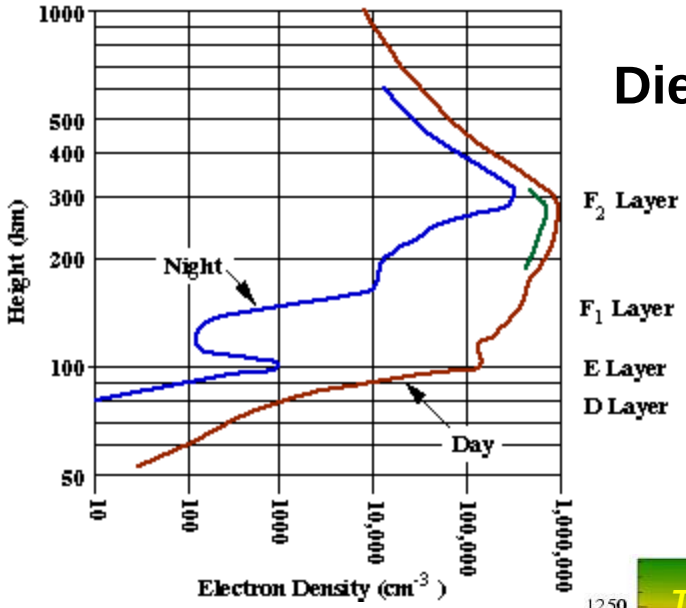
Overview

- **Introduction**
  - **Rationale**
  - **C/NOFS mission, satellite sensors**
  - **C/NOFS results**
    - **~100 peer reviewed articles published about C/NOFS → can only glance at a few results**
- **Science results related to ambient ionosphere, plasma irregularities, scintillations and modeling**
- **Future plans**
- **Discussion /conclusions**



Introduction
Rationale ("Ionosphere 101")

Formed by solar EUV/UV radiation

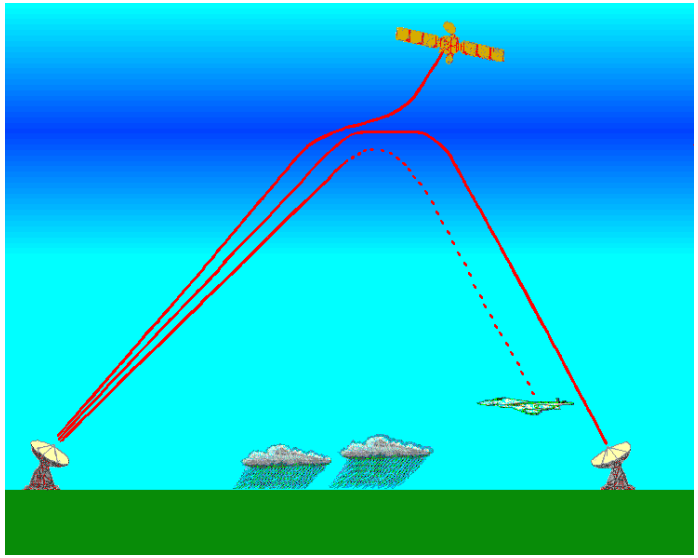


Dielectric Properties

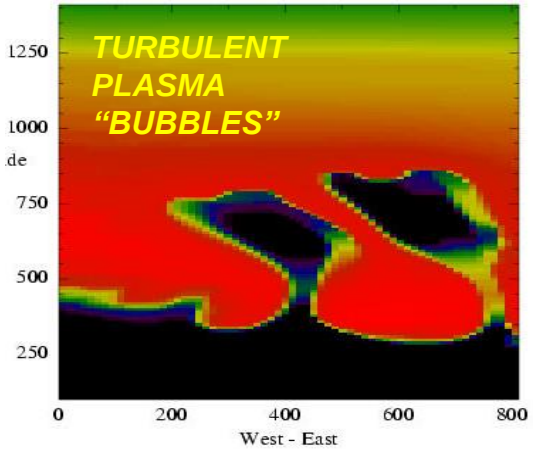
$$\varepsilon = \left(1 - \frac{f_p^2}{f^2}\right)\varepsilon_o$$

$$f_p \approx 9 \cdot 10^3 \sqrt{n_e}$$

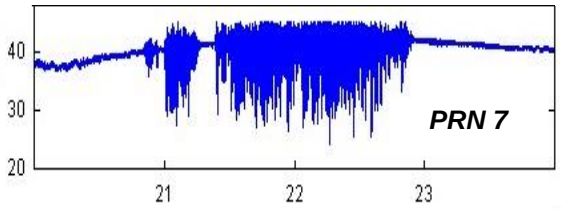
Reflects, refracts, diffracts & scatters radio waves, depending on frequency, density, and gradients



Subject to Raleigh-Taylor instability at night →formation of Equatorial Plasma Bubbles (EPBs)



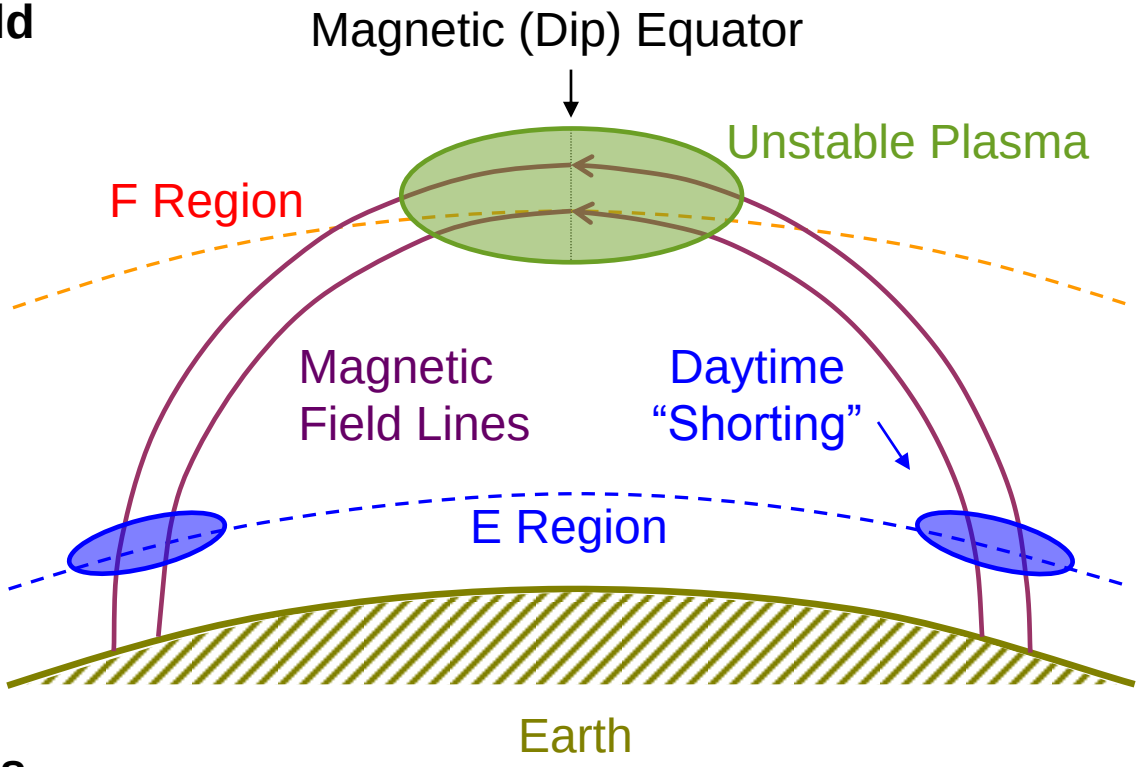
Leads to highly variable reflection / refraction = "SCINTILLATION"

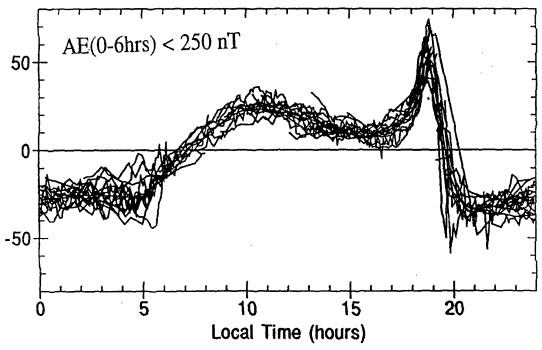


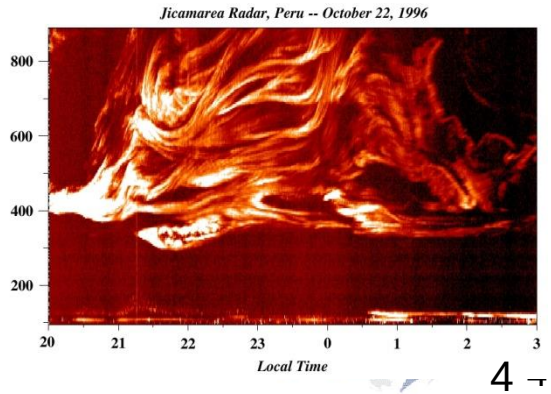
Scintillated GPS Signal

Introduction
Equatorial Plasma Bubbles

- **Plasma moves easily along field lines**
- **Upward plasma drift supports plasma against gravity ⇒ unstable configuration**
- **E-region "shorts out" electrodynamic instability during day**
- **At night, E-region conductivity too small to short-out E field**
- **Instability in plasma grows to form equatorial plasma bubbles (EPBs), which contain irregularities seen by radars (right image) & which disrupt communications**
- **Irregularities mainly present during quiet times**





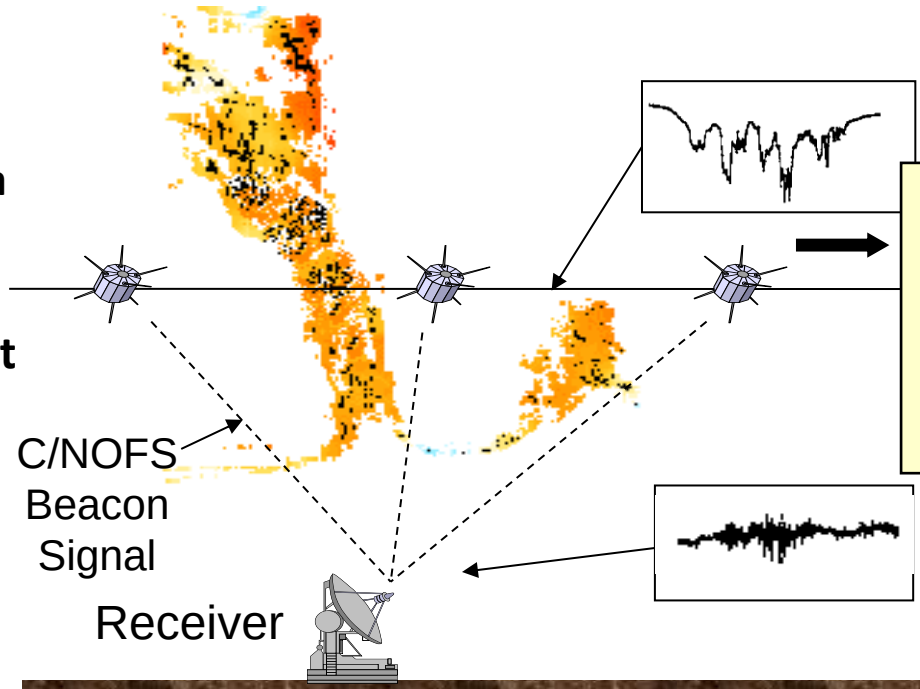


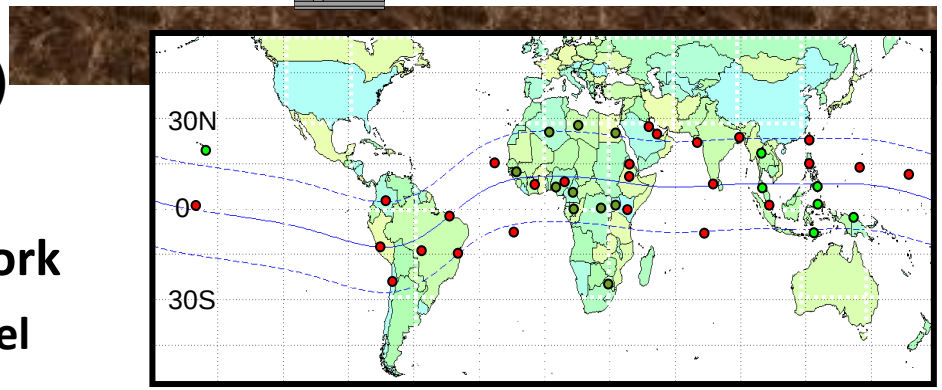
Introduction

Communication/Navigation Outage Forecasting System (C/NOFS) Mission

Mission Components

- **Satellite, w/ 6 sensors:**
  - ***In situ*** **ion density from Plasma Langmuir Probe (PLP) (AFRL)**
  - **Electric and mag fields from Vector Electric Field Instrument (VEFI) (NASA)**
  - **Ion Velocity, composition, Ti from Ion Velocity Meter (IVM) (UTD)**
  - **Neutral Wind Meter (NWM) (UTD)**
  - **GPS Radio Occultation (CORISS) (Aerospace)**
  - **HF Beacon (CERTO) (NRL)**
- **Ground-based SCINDA Network**
- **Models i.e. Physics-Based Model (PBMod) & several others**
- **Data Center**



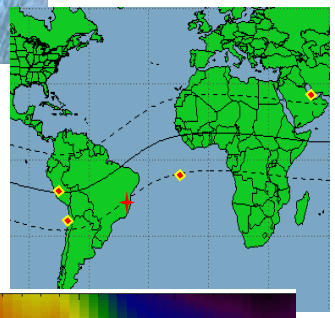


Scintillation Network Decision Aid (SCINDA)

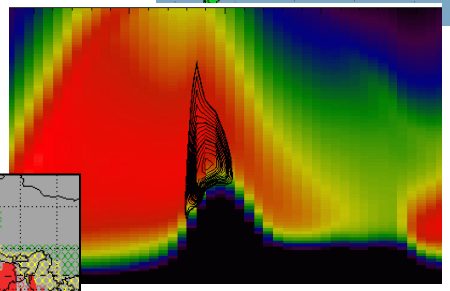
Introduction
C/NOFS Program Goals

- **Develop technology for specifying & forecasting:**
  - **Scintillation effects on UHF-SATCOM , GPS systems & surveillance radars**
  - **Electron density profile influence on geolocation, surveillance systems**
- **Establish effectiveness of space-based measurements**
- **Build and validate ionosphere models**
- **Provide system impact decision aids to DoD users**
- **Expand scientific understanding of ionosphere, dynamics, and iono effects on radio wave propagation**

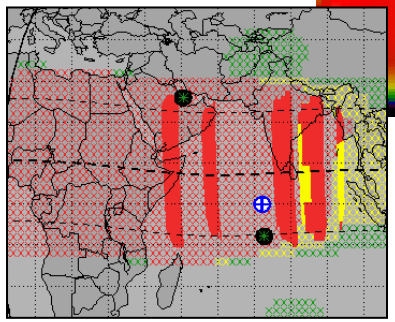
Space-Based Data Sources



Ground-Based Data Sources



Forecast Modeling

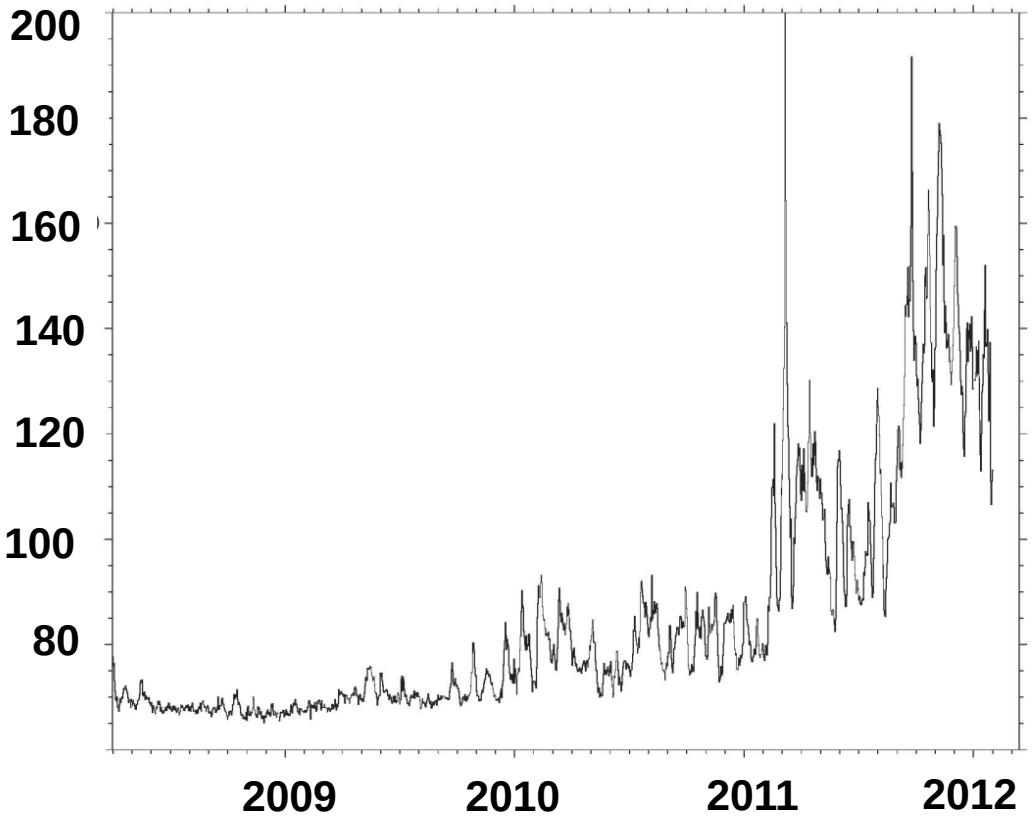


Warfighter support decision aids

Introduction

Solar Activity During C/NOFS

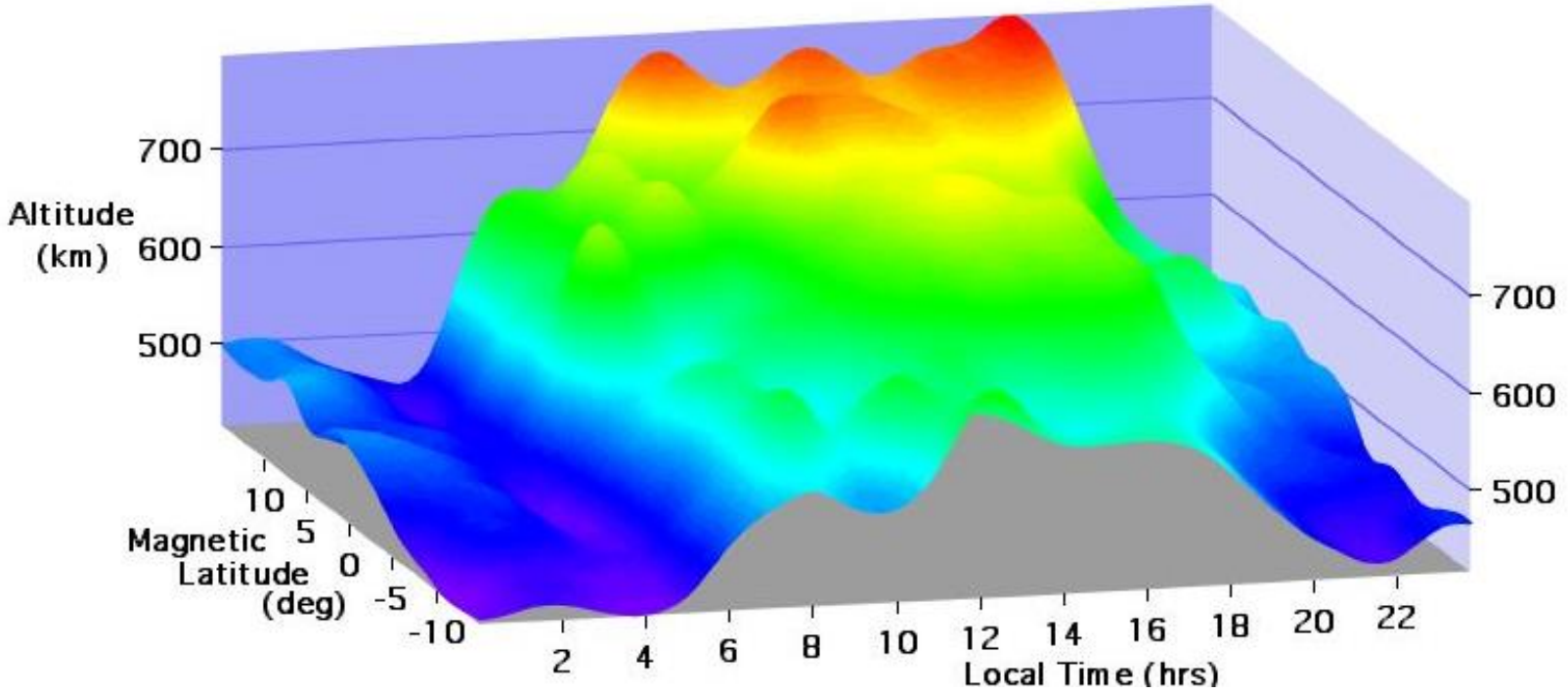
F10.7 during C/NOFS lifetime



- Based on F10.7, 2008 and 2009 were extremely quiet -- the lowest ever measured
- In 2010 F10.7 increased moderately
- In 2011 larger increase
- In 2012 solar cycle might have peaked

Low solar activity sparked important discoveries on ion densities & plasma irregularities

Ambient Ionosphere During Extreme Solar Min



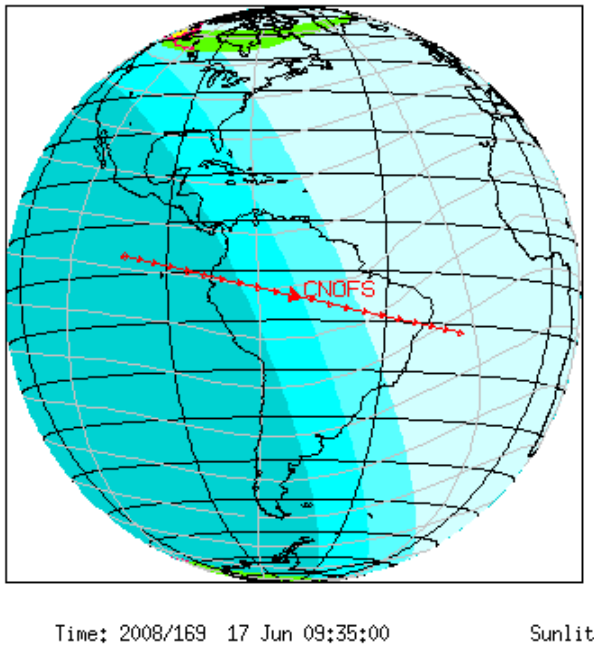
- **O+/H+ transition height ~ 200 km lower than IRI predicts**
- **Peak daytime ion temp 1,000 K cooler [From Heelis et al., 2009]**

"Space is just a little bit closer"

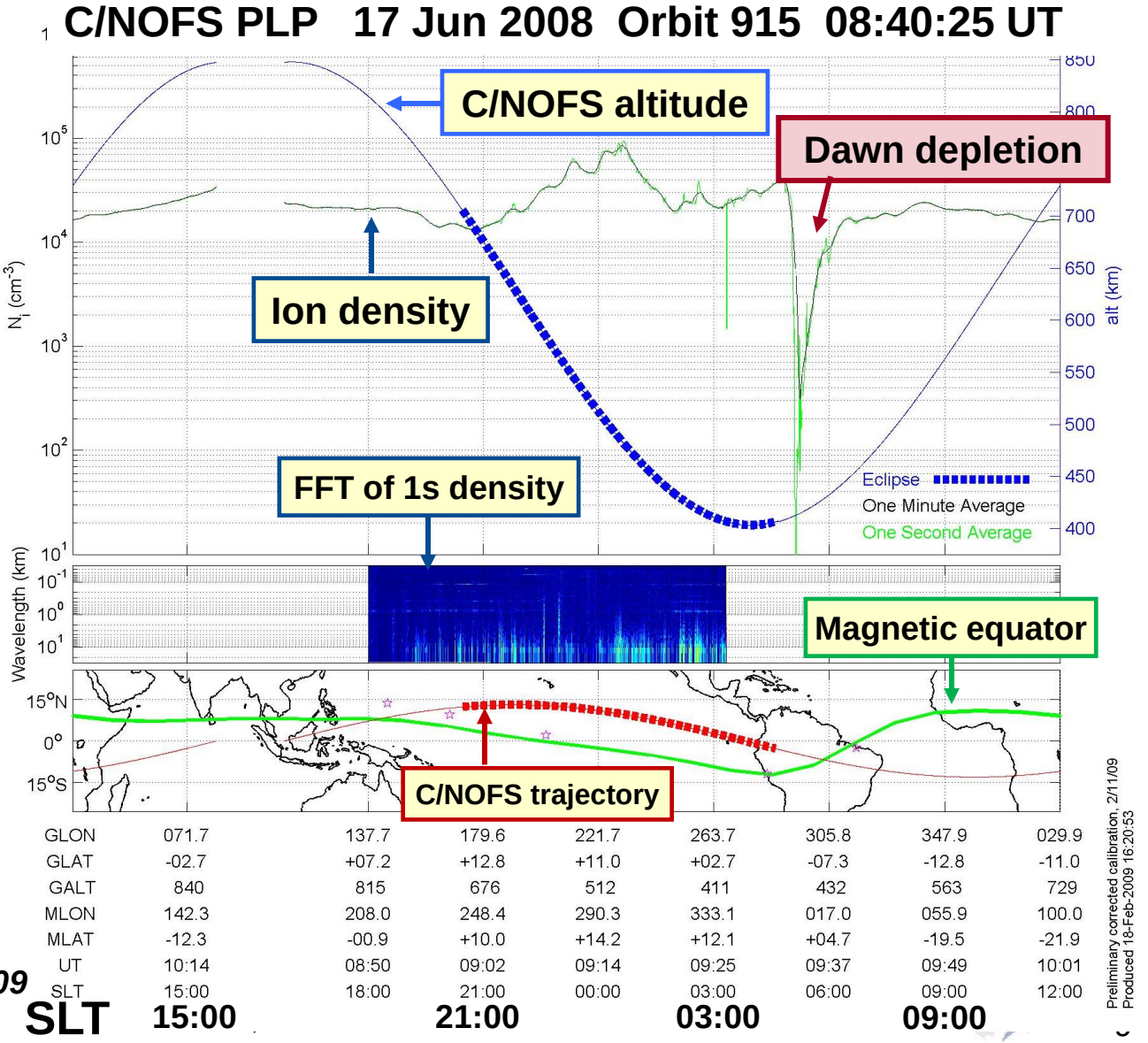
[BBC headline on C/NOFS]

C/NOFS Observations of Dawn Depletion

- Unexpected deep depletion in electron density at ~05:00 LT
- Just before sunrise

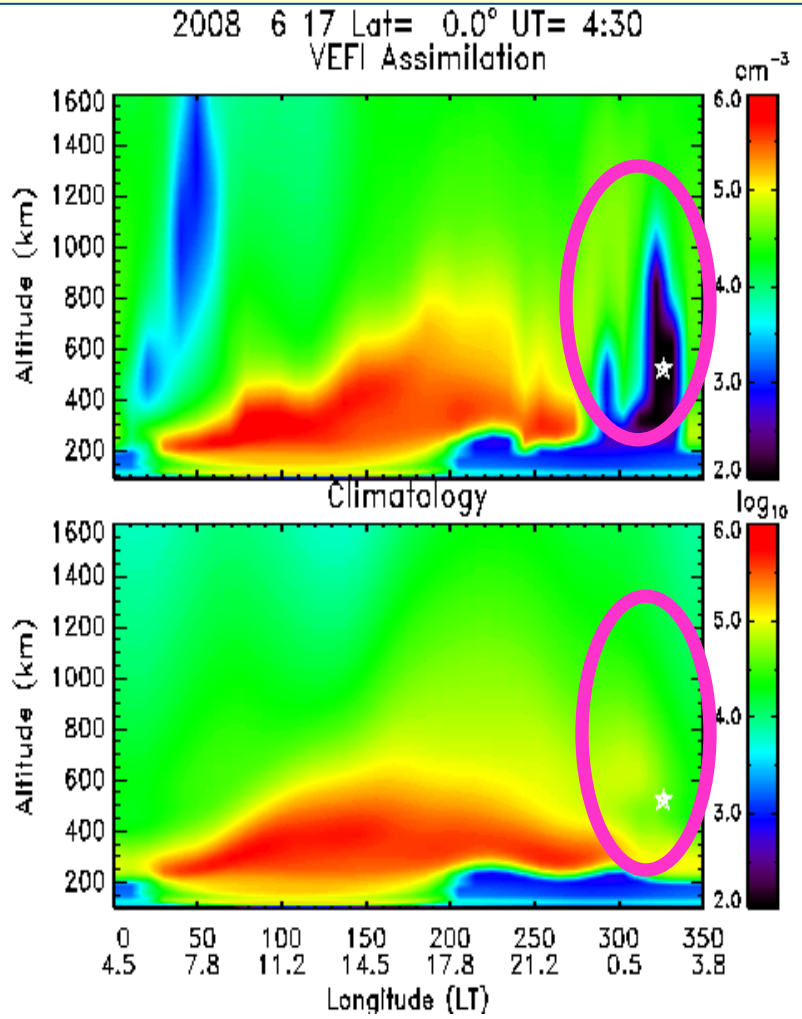


de La Beaujardière et al., GRL, 2009



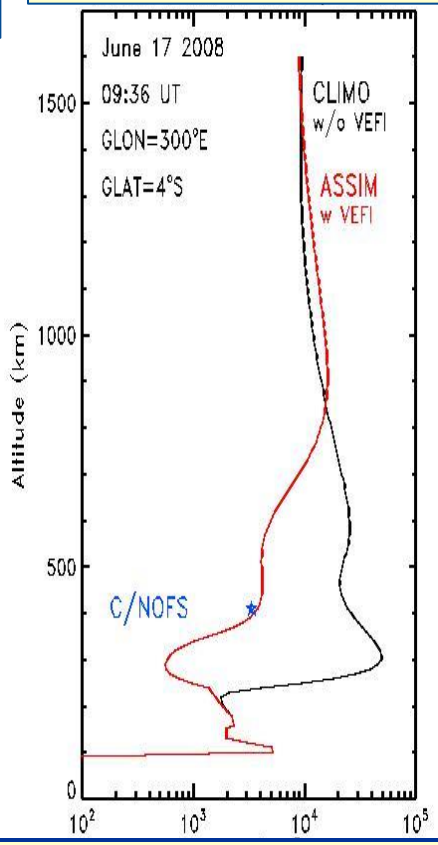
Modeling the Ambient Ionosphere

Electron density profiles (EDP), fixed UT, all longs



[From Su et al., 2009]

(EDP), fixed UT & long



Top Left: EDPs calculated from Physics Based Model (PBMod) using C/NOFS E-field

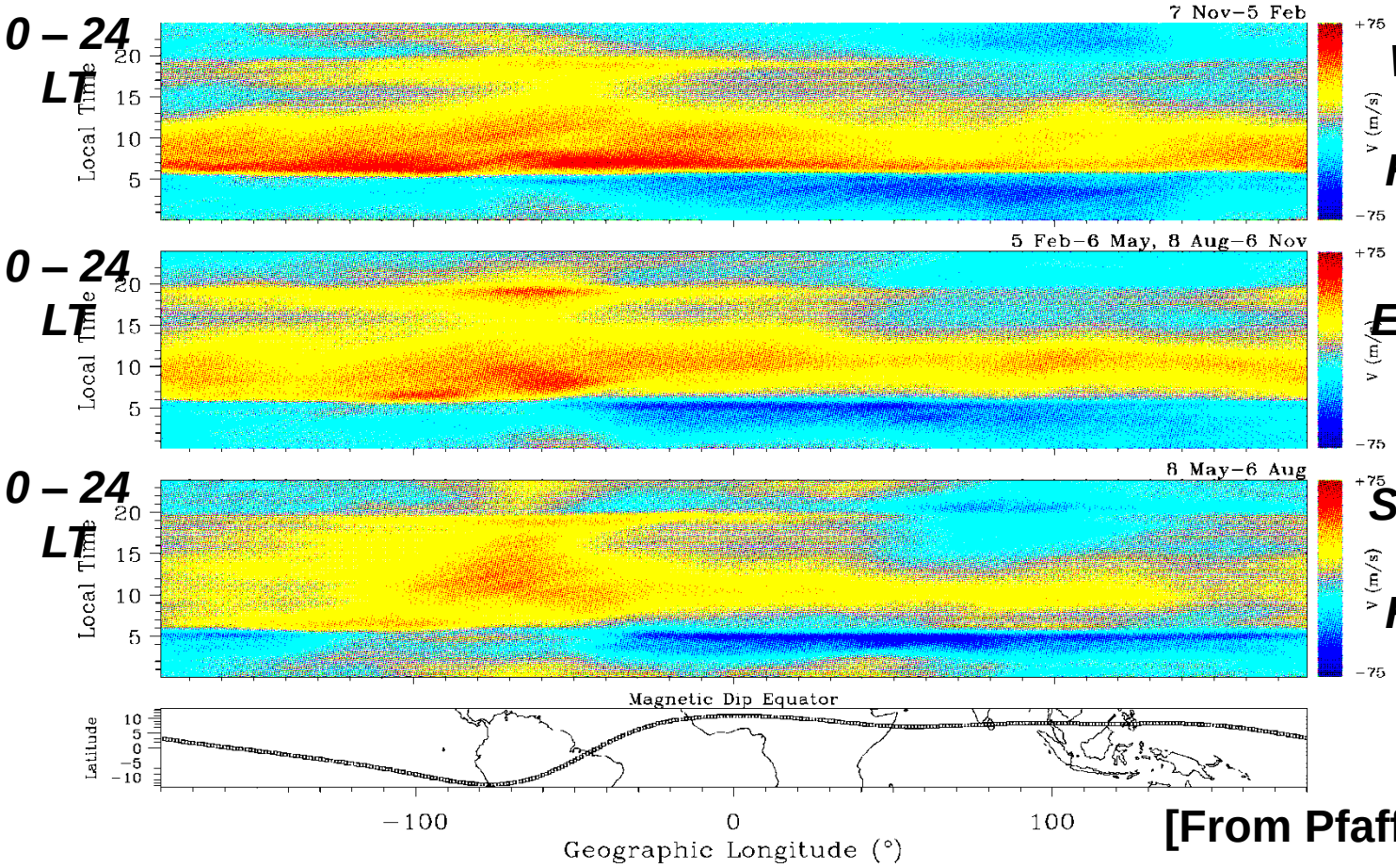
Bottom Left: Same but using climatological E-Field

Right: EDP calculated using actual E-Fields (red) and climo (black).
Star indicates C/NOFS position and its measured density – model & data are in perfect agreement.

C/NOFS detected deep N_i minima close to dawn, which were often associated with plasma irregularities. N_i minima well modeled with PBMod

Average E-fields from VEFI
Meridional component

E x B meridional Drifts -- +/– 5 deg of Mag Equator; 9 May 2008 – 5 Feb 2011



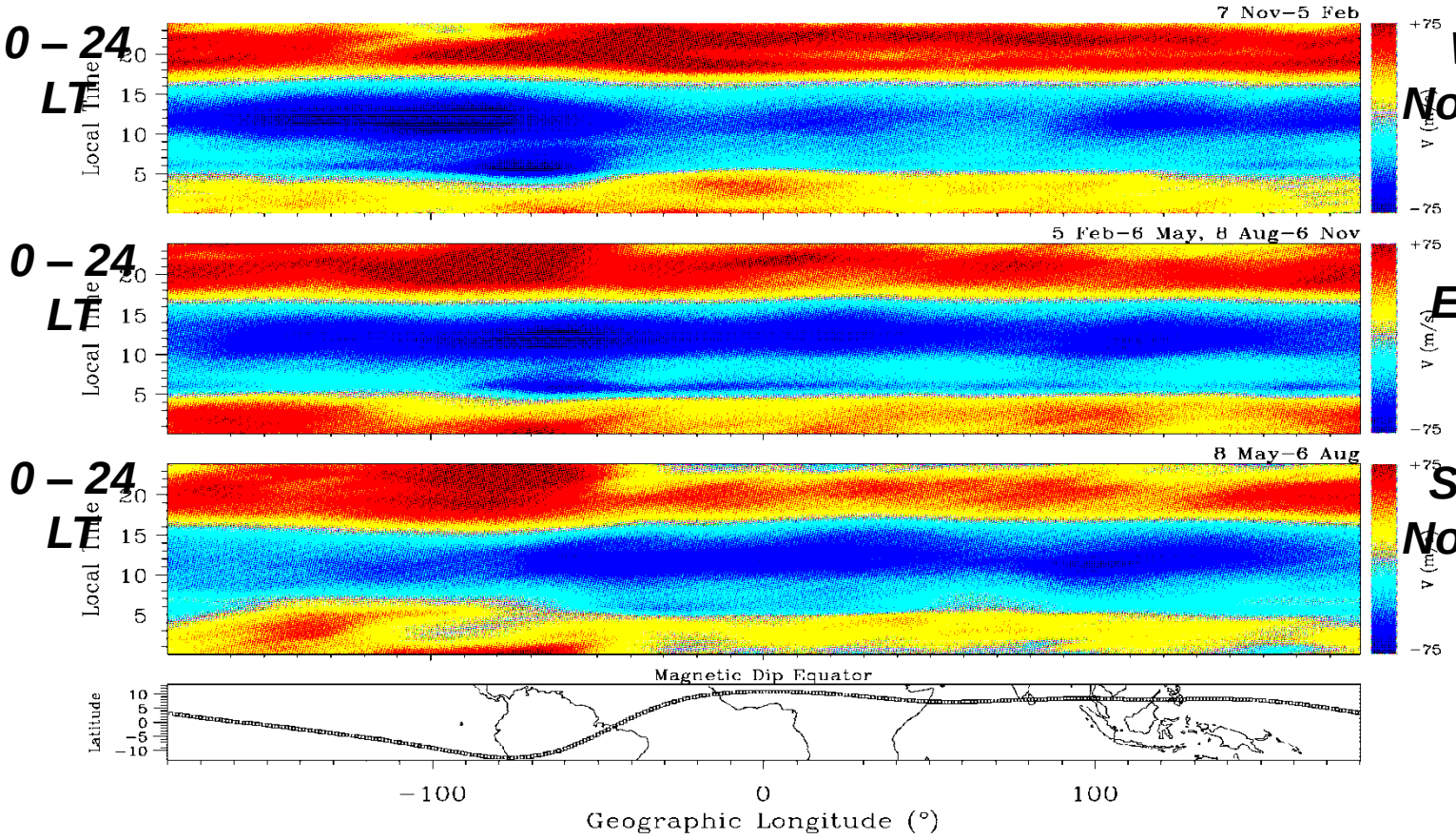
[From Pfaff, 2012]

Large dependence on longitude and season

Average E-fields from VEFI

Zonal component

E x B zonal Drifts -- +/– 5 deg of Mag Equator; 9 May 2008 – 5 Feb 2011

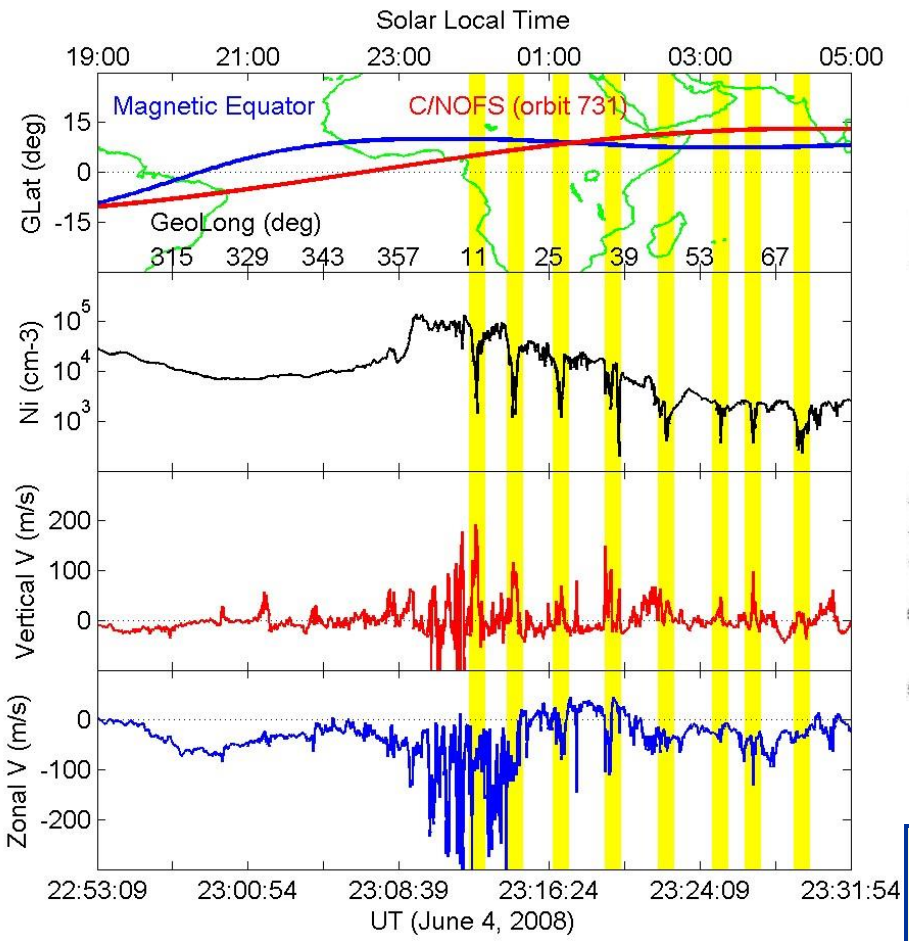


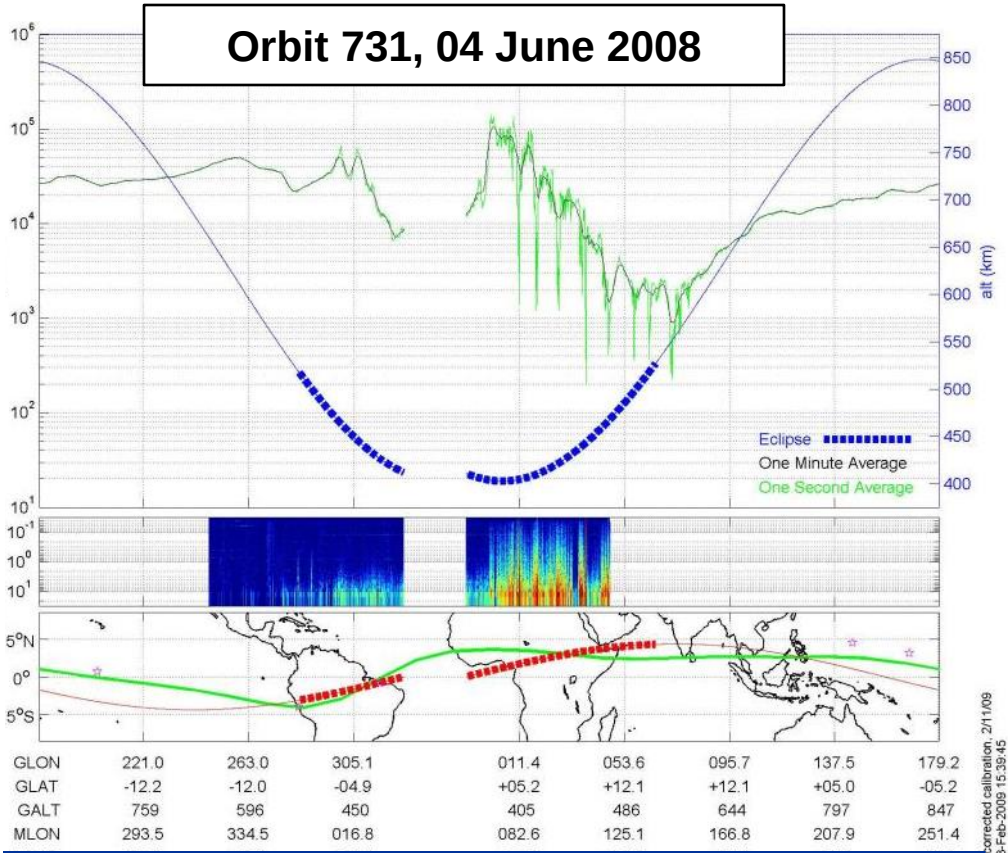
[From Pfaff, 2012]

Large dependence on longitude and season

Equidistant EPBs

Example of EPB formed after midnight
Upward ion velocity reaches 200 m/s in first EPB

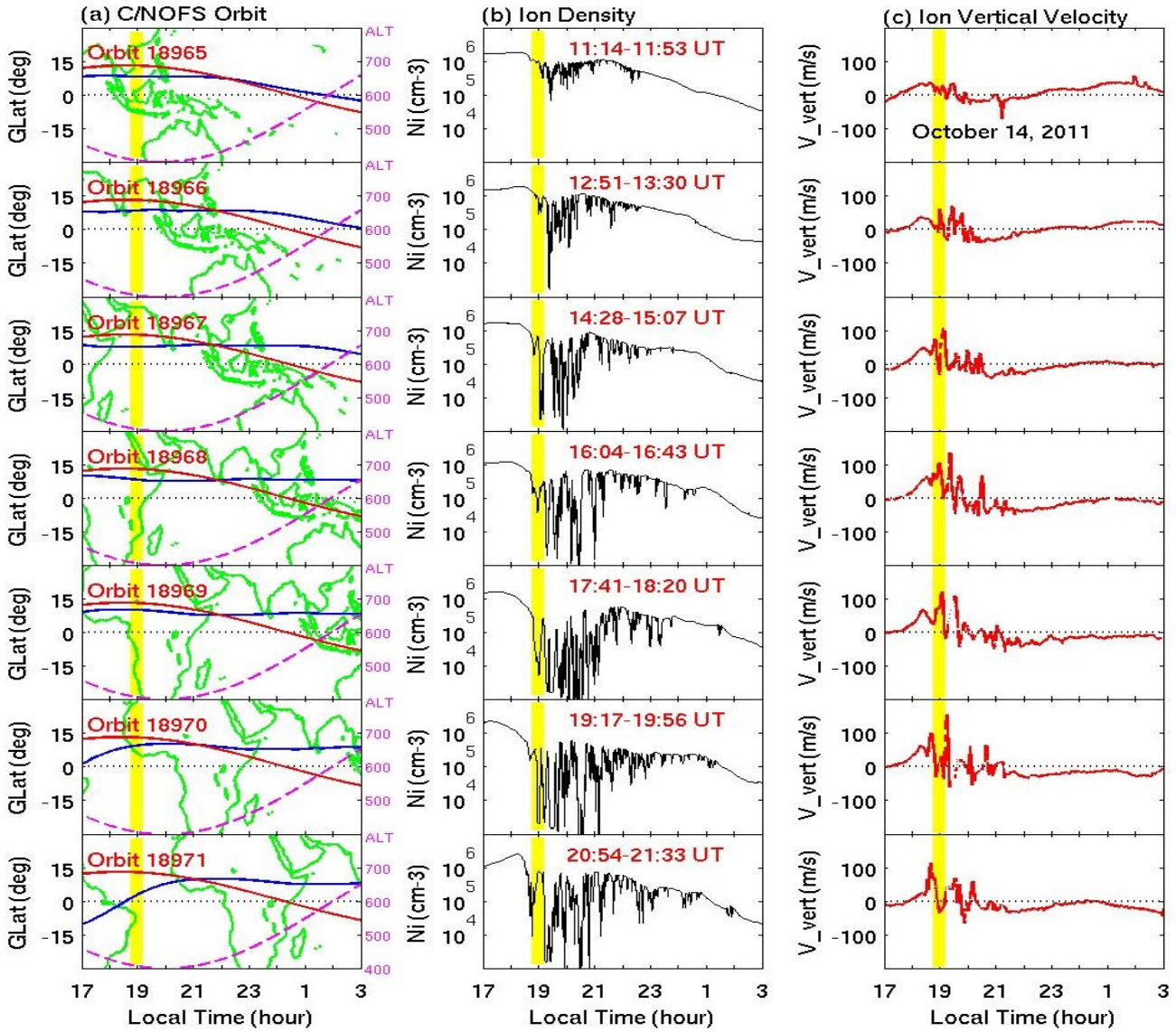




Almost equidistant EPBs separated by 8.5º (~950 km)
Question: How were they formed?

From Huang et al., JGR, 2012

Plasma Bubbles Generated Near Sunset

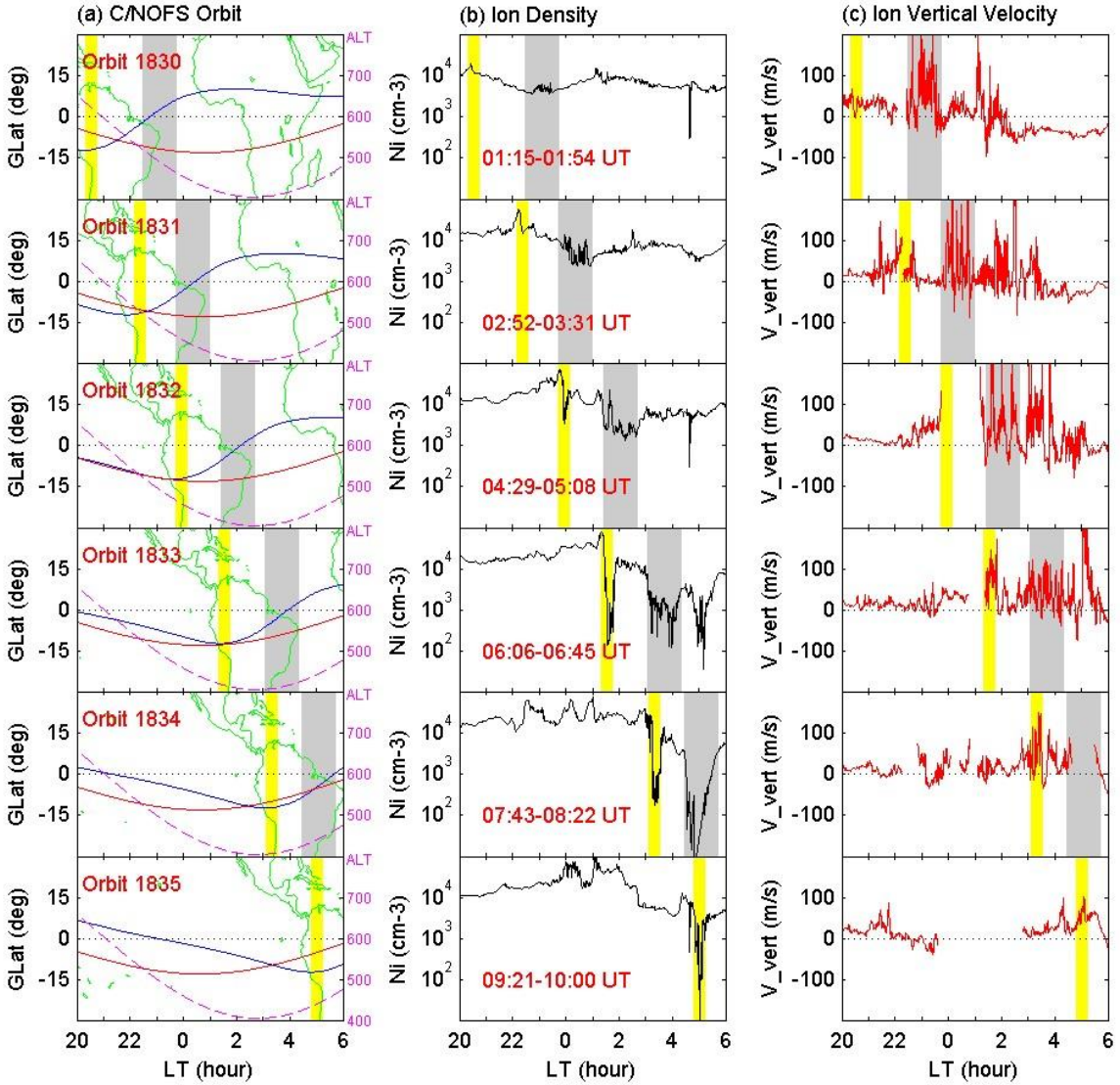


[From Huang et al., 2012a]

Oct 14, 2011 example:

- **EPBs continuously generated at sunset over ~19 hrs**
- **Presence of upward ion drift (Pre-reversal enhancement) main factor in EPB formation**

Long-lasting Plasma Bubbles



[From Huang et al., 2012b]

EPBs generated in the evening sector

Become fully developed after midnight.

Last for >7 hours

Velocity within EPBs upward

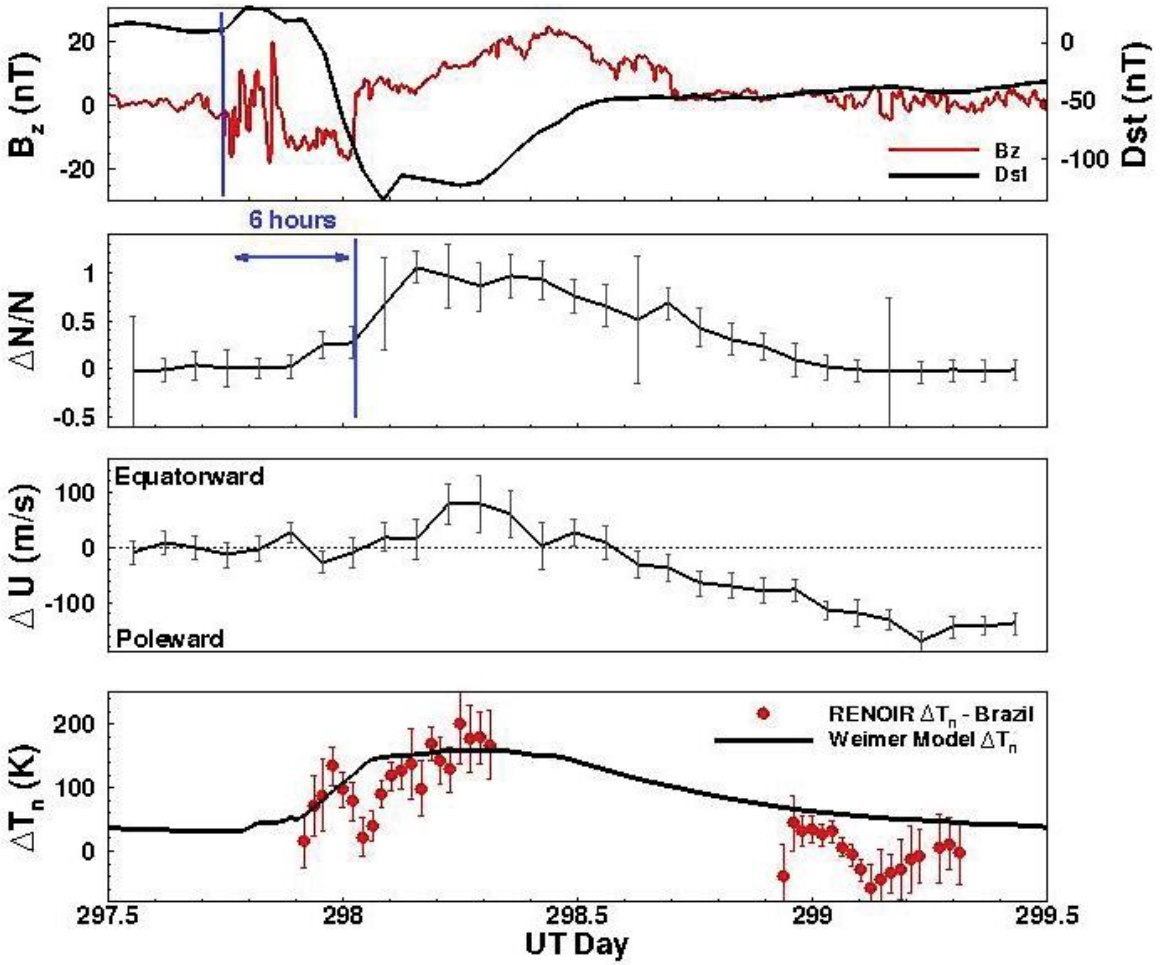
Stay at the same longitudes

Irregularity decay-rate can be inferred from these C/NOFS measurements

(August 18, 2008)

Wind Measurements from C/NOFS

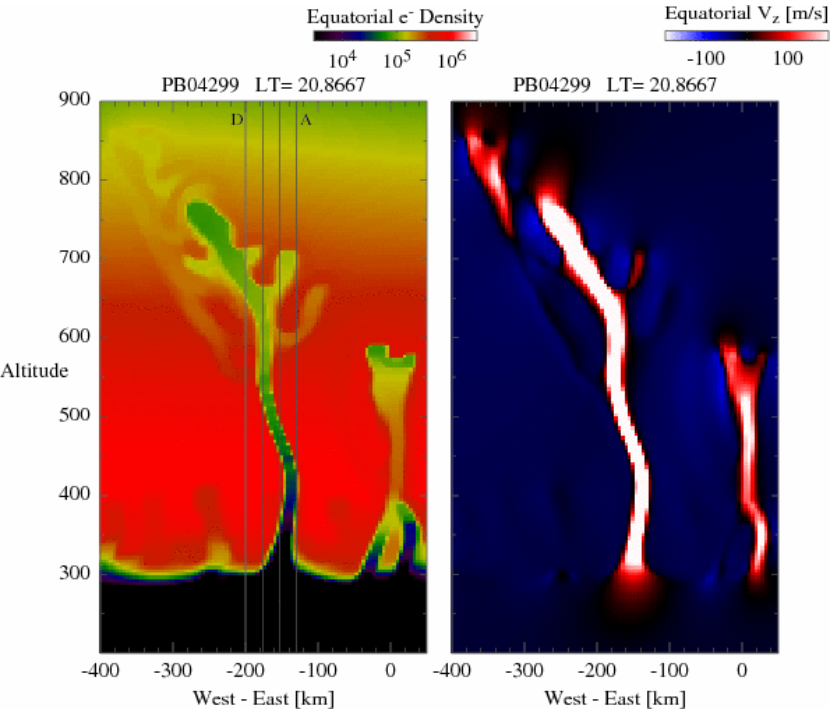
Neutral wind measurements, October Storm: 2250-0035 SLT



- Only in 2012 was thermosphere dense enough to measure winds
- 100% increase in neutral density at end of storm main phase
- Cross track wind increased by 100 m/s during storm main phase
- C/NOFS values match FPI measurements (not shown)
- Neutral temperature increased by ~200^0

[From Earl et al., 2013]

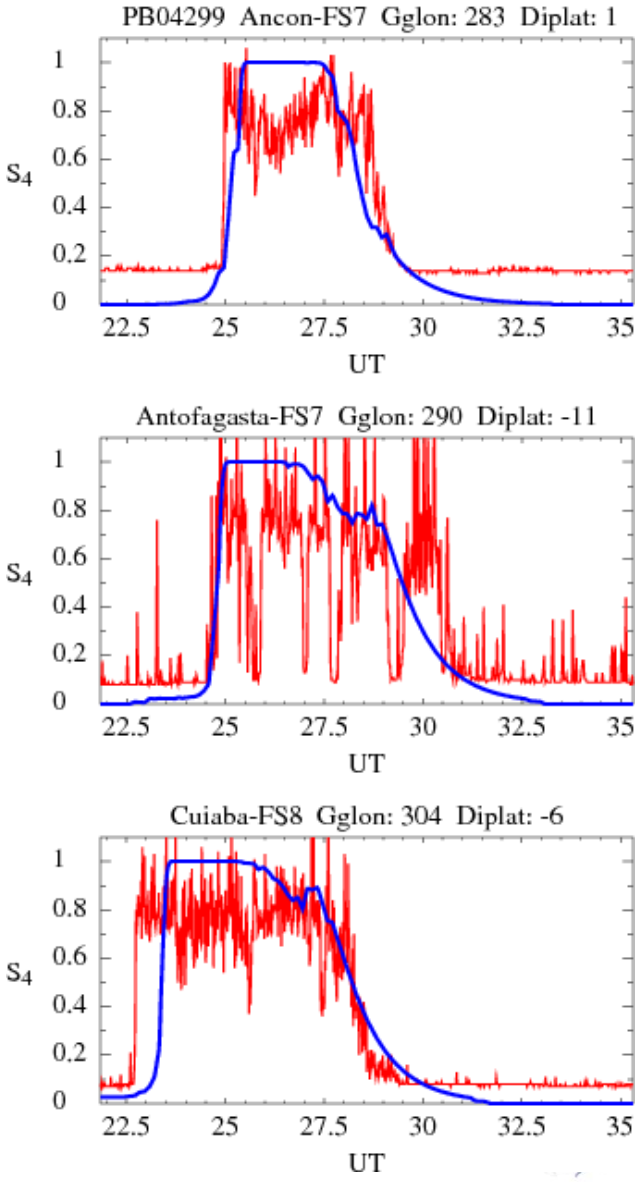
Scintillation Modeling by PBMOD



Plume structure in density (left) and vertical velocity (right)

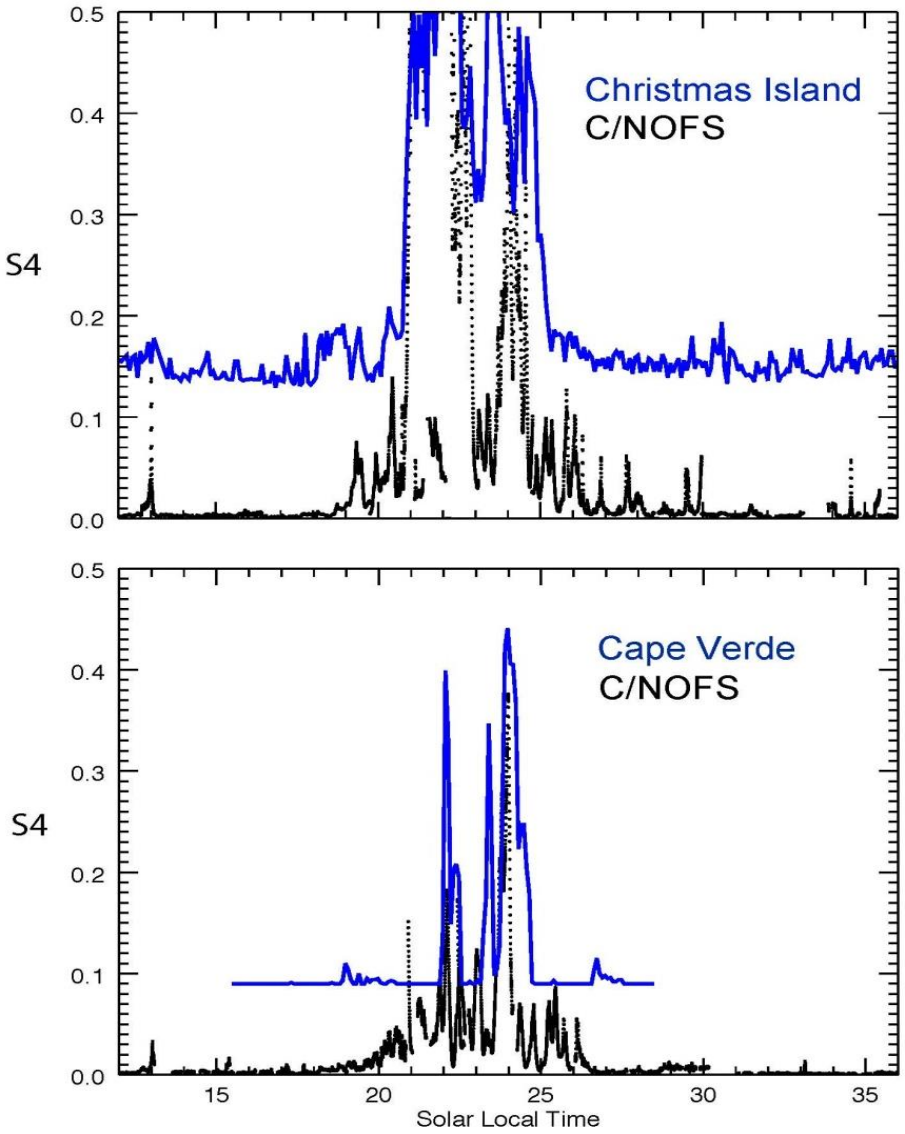
[From Retterer 2010 a,b]

Scintillation observed at 3 SCINDA stations (red) compared with PBMOD predictions (blue)



EPB formation and scintillation estimated using Physics Based Model (PBMod)

Estimating Scintillation Using Wavelets



[From Stoneback et al., 2013]

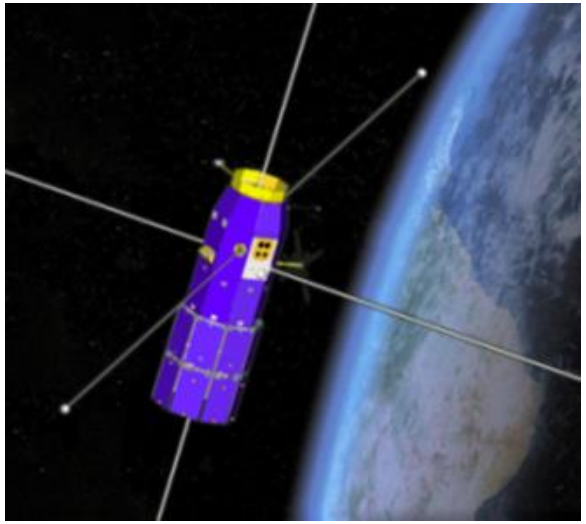
- New & promising method to estimate scintillation index from C/NOFS data
- Developed by R. Stoneback (UTD)
- Based on Wavelets decomposition of ion density

- Plot shows:
  - S4 at 250 MHz from ground-based SCINDA stations at Christmas Island and Cape Verde (blue curve)
  - Estimate from C/NOFS (black curve)
  - Nov 6, 2009

Future

- C/NOFS sensors still working perfectly
- Severe budget cuts threatening the satellite
- Mission might be terminated in June 2013 or satellite "mothballed" until its orbit more circular

- Operational follow-on scheduled 2016
  - COSMIC 2 constellation of 6 satellites
  - Partnership with NSPO (Taiwan), AF, NOAA
  - 24° inclination, 550 km altitude
  - Instruments provided by US AF:
    - Ion velocity meter (VIDI)
    - Ionospheric beacon
    - Occultation sensor (Tri-band GNSS Receiver System, for GPS, Galileo, GLONASS signals…)

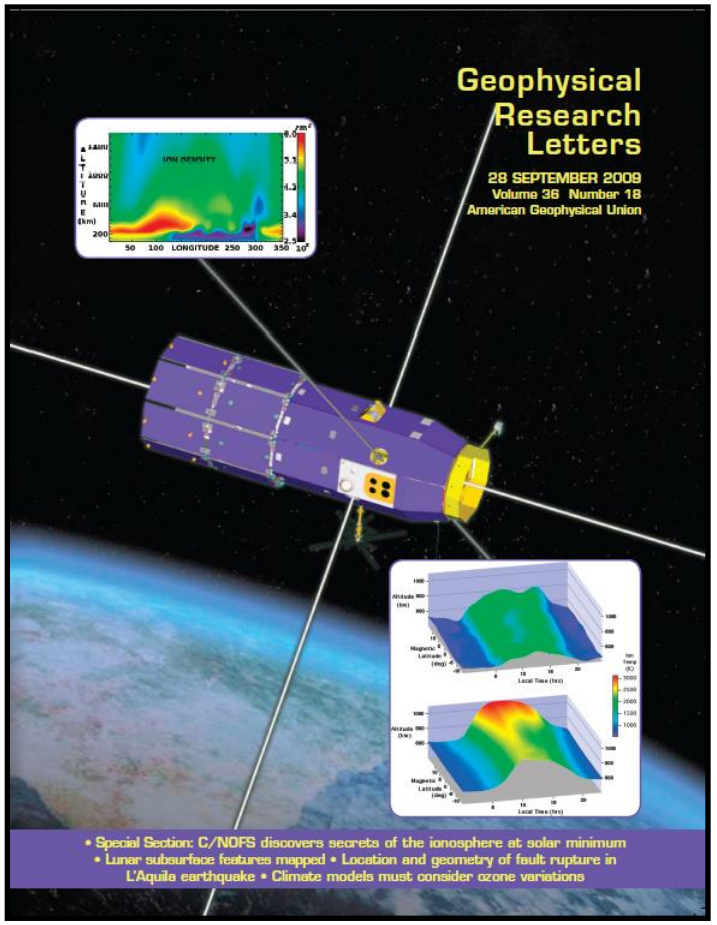


Discussion/Conclusion

- C/NOFS satellite 13° inclination, elliptical orbit
- Launched in April 2008 during lowest solar min in 100 yrs.
- Mission goals
  - Specify and forecast Scintillation and Electron Density Profiles
- During deep solar minimum:
  - Ambient ionosphere and thermosphere are lower and colder than ever recorded
  - Pre-reversal enhancement at dusk very rare
  - EPBs detected mostly post midnight
  - Deep and narrow ionospheric depletions seen close to dawn; are well modeled
- C/NOFS low inclination allows observations close to equator at all longitudes
  - EPBs continuously generated at sunset (when solar activity increased)
  - Continuous observations of same EPBs throughout the night
  - Equidistant EPBs detected
    - Separated by ~1000 km

Discussion/Conclusion

- **Wind and thermosphere measurements only now possible**
  - **Reveal changes associated with mag storms**
- **Scintillation index estimated from 2 different methods**
- **~100 C/NOFS publications written (list available)**
- **GRL Special Issue came out in 2009**
- **Annales Geophysicae special issue planned**
  - **Articles due soon**
  - **Jeff Klenzing (NASA) leader**



Cover of GRL Special Issue on C/NOFS (2009)

Thank you
Merci
Gracias

The C-NOFS Satellite

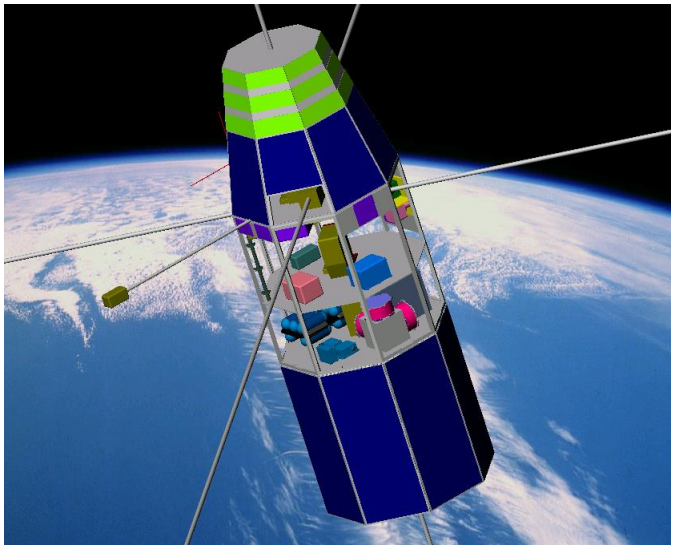
GPS Receiver

C/NOFS Occultation Receiver for Ionospheric Sensing and Specification (CORISS)

- Developed by Aerospace (P. Straus PI)
- Measures: Remote sensing of LOS TEC

Planar Langmuir Probe (PLP)

- Developed by AFRL/VS (D. Hunton PI)
- Measures: Ion Density, Ion Density Variations, Electron Temperature



Electric Field Instrument

Vector Electric Field Instrument (VEFI)

- Developed by NASA/GSFC (R. Pfaff PI)
- Measures: Vector AC and DC electric as well as magnetic fields
- Includes lightning detector

Ion Velocity Meter (IVM)

- Developed by Univ. of Texas Dallas (R. Heelis PI)
- Measures: Vector Ion Velocity, Ion Density, Ion Temperature

Neutral Wind Meter (NWM)

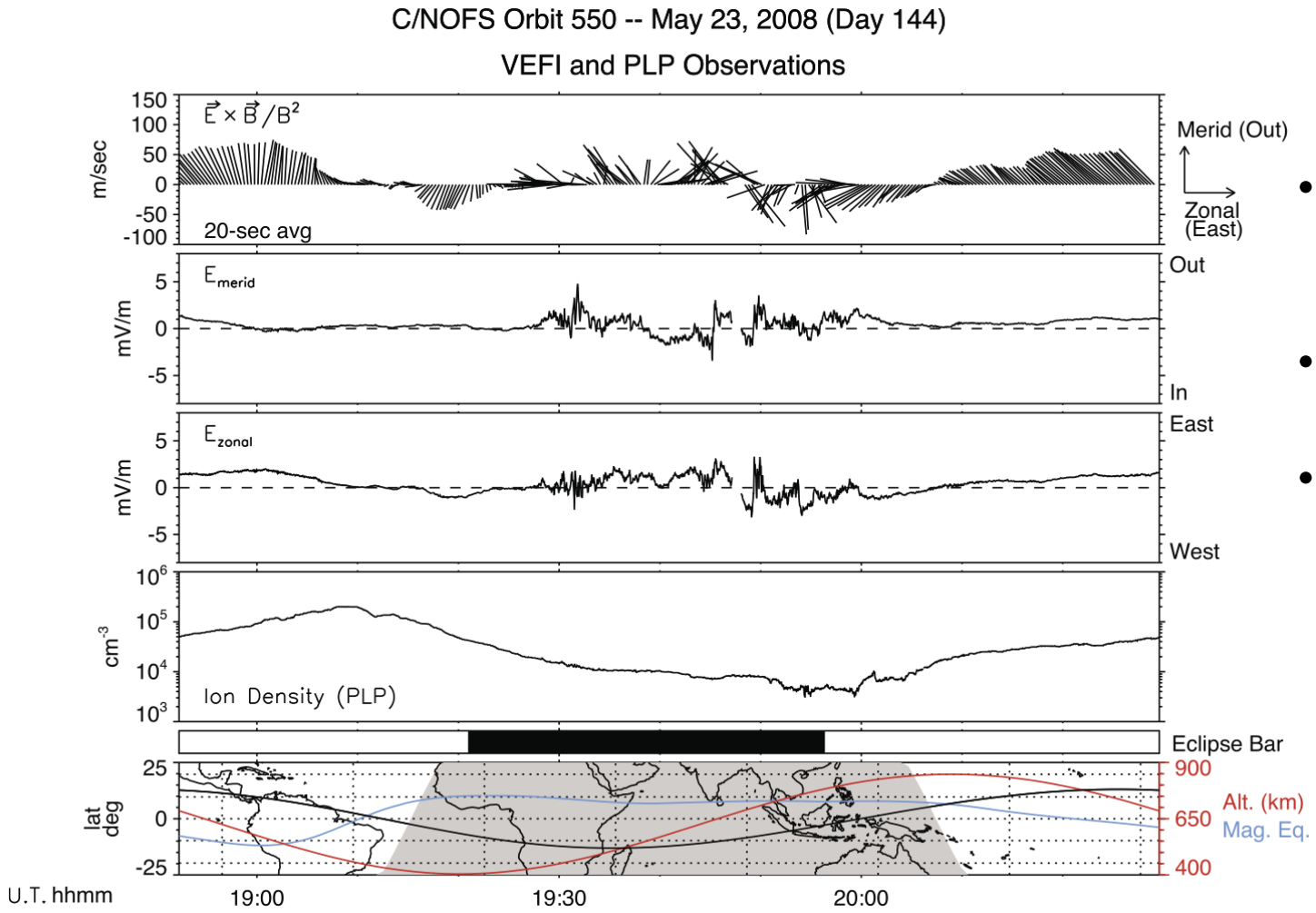
- Developed by Univ. of Texas Dallas (G. Earle PI)
- Measures: Vector Neutral Wind Velocity

RF Beacon

Coherent EM Radio Tomography (CERTO)

- Developed by NRL (P. Bernhardt PI)
- Measures: Remote sensing of RF scintillations and LOS TEC

Electric Field Patterns



- **Smooth Velocities during day**
- **Perturbed at night**
- **In this pass, E field perturbed even though plasma density is not**

[From Pfaff et al., 2010]