Small Scale Ionospheric Irregularities
(and their effects on radio wave propagation)

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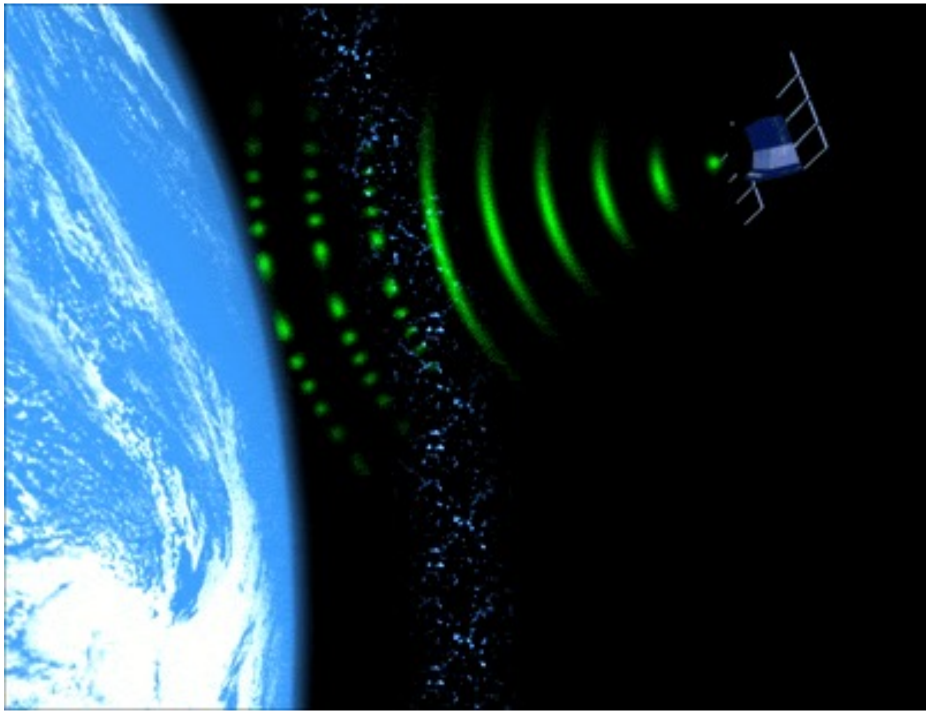
Overview

- Ionospheric irregularities can cause disruptive effects on radio wave propagation that can impact space-based radio frequency services such as communications and navigation (GNSS).
- Principal regions affected include high and low latitudes; mid-latitudes are vulnerable during magnetic storm periods.
- We focus on the equatorial region here (the most severe environment) and the underlying dynamics that give rise to intense irregularities.
- Most existing methods for detecting irregularities utilize dedicated ground-based GNSS and other receivers specialized to measure rapid signal fluctuations from satellites.
- Newer methods measure GNSS signals from low-earth orbiting satellites (radio occultation) to obtain global coverage over land and sea; we will discuss that on Thursday.

Outline

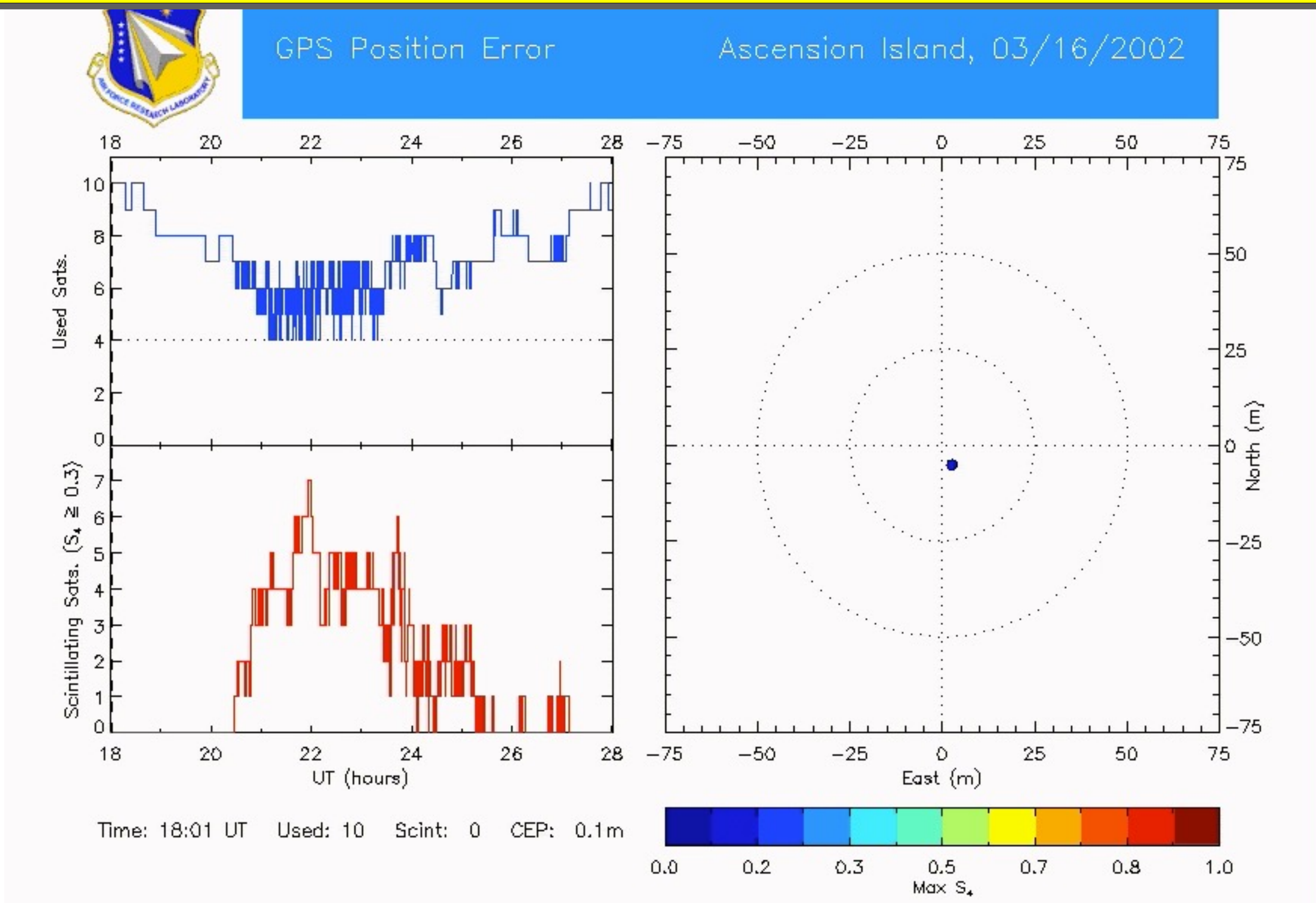
- Motivation: Why do we care about small-scale irregularities?
- Brief review of plasma and radio physics: scintillation
- The characteristics of irregularities that affect GNSS signals
- Where are such irregularities found and why?



Courtesy C. Miller, Bath University

Why Do We Care About Ionospheric Irregularities Anyway?

Scintillation can cause rapid fluctuations in GPS position fix;
Typical night from field experiments in 2002



Ionospheric Irregularities & Scintillation Physics

- A uniform ionosphere slows radio waves but does not distort amplitude and phase.
- Electron density irregularities introduce phase variations on the wavefront from the satellite causing a diffraction pattern on ground.
- Interference pattern changes in time and space, such that a user observes rapid fluctuations of signal amplitude and phase that degrade system performance.

Time Delay:

$$\tau_d = R/c + \frac{r_e c}{2\pi}\frac{N_{tot}}{f^2}$$

Phase Advance:

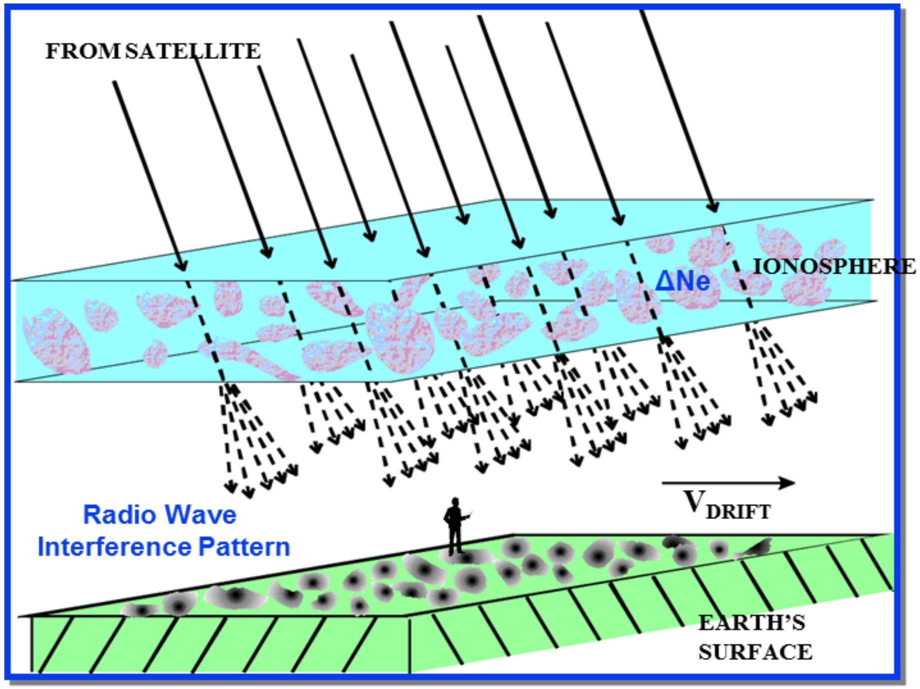
$$\delta\varphi = 2\pi f R/c - r_e c \frac{N_{tot}}{f}$$

ionospheric contribution

Depends on TEC:

$$N_{tot} = \int N_e(z)dz$$

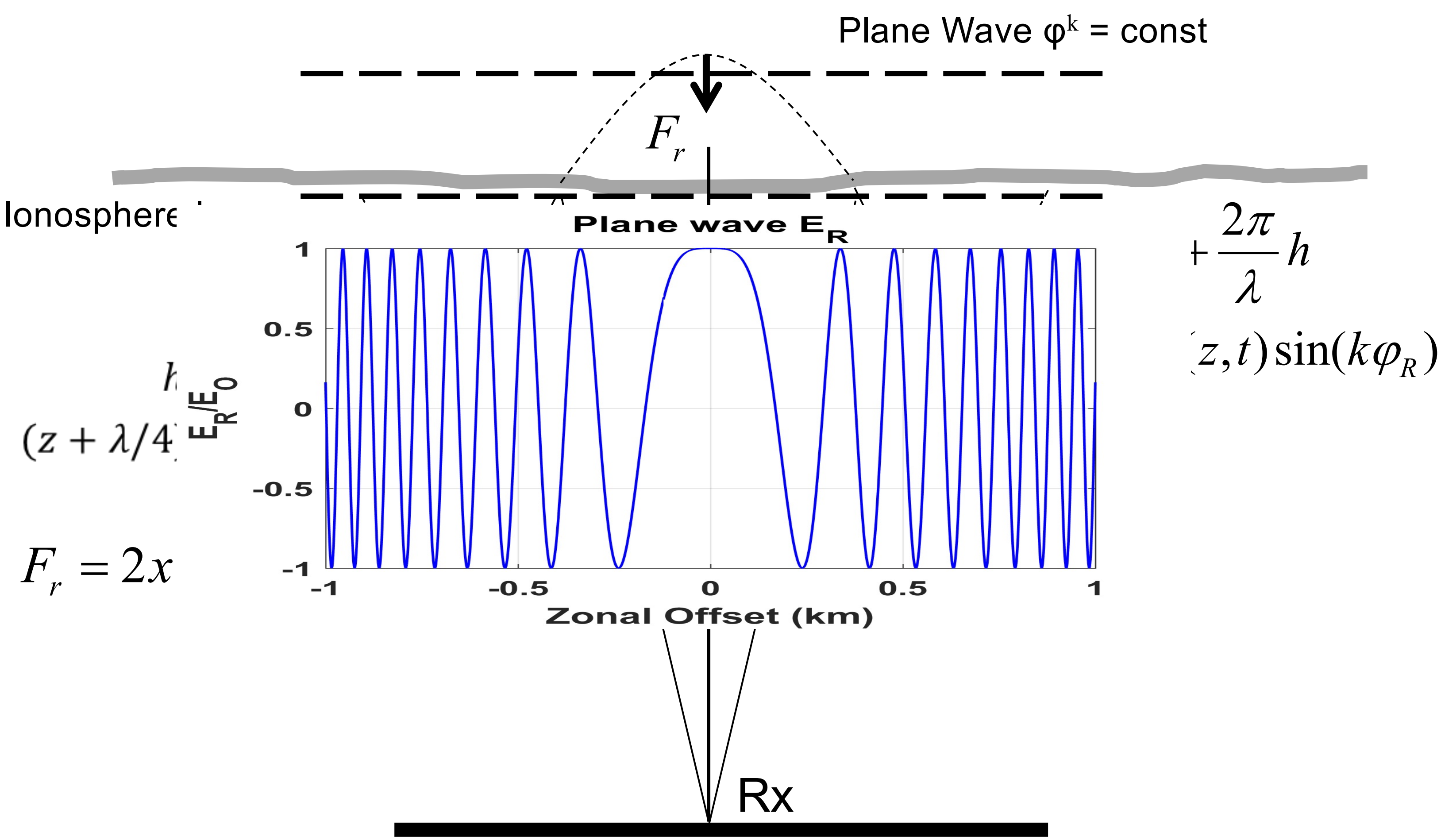
$$\delta\varphi \approx 5 \times TEC \text{ radians}$$



Destructive interference requires a phase change of π radians, equivalent to 0.6 TEC units. But the change has to occur within a relatively short distance known as a Fresnel scale defined by $F_r = 2x = \sqrt{2\lambda z}$

How Small Must the Irregularities Be?

Graphical Depiction of the Fresnel Scale



- The distance over which scattering contributions contribute “in phase” at the receiver
- For GPS L1 frequency, F_r is typically 400-500 meters; density fluctuations larger than this scale size will not cause GNSS amplitude scintillations.

The Ionosphere is a Small Perturbation for GNSS

$$v_\varphi = \frac{\omega}{k} = \frac{c}{n}$$

$$n = \sqrt{1 - \frac{f_p^2}{f^2}}$$

$$f_p \sim 10\ MHz$$

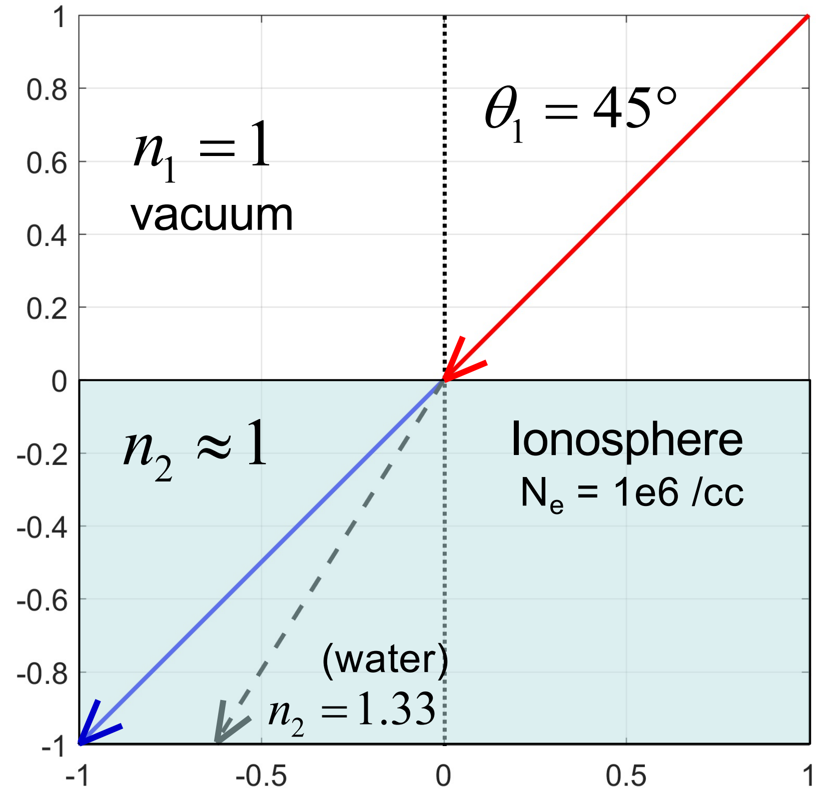
$$f = 1575 MHz$$

$$\boxed{f_p^2 / f^2 \approx 4\times 10^{-5}\ !!}$$

Snell's Law:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

For the parameters shown at right, the change in angle is 0.001° (20 μrad)! Can you see it?



Perturbation to index of refraction is very small, yet it is enough to cause serious propagation effects: the power of diffraction!

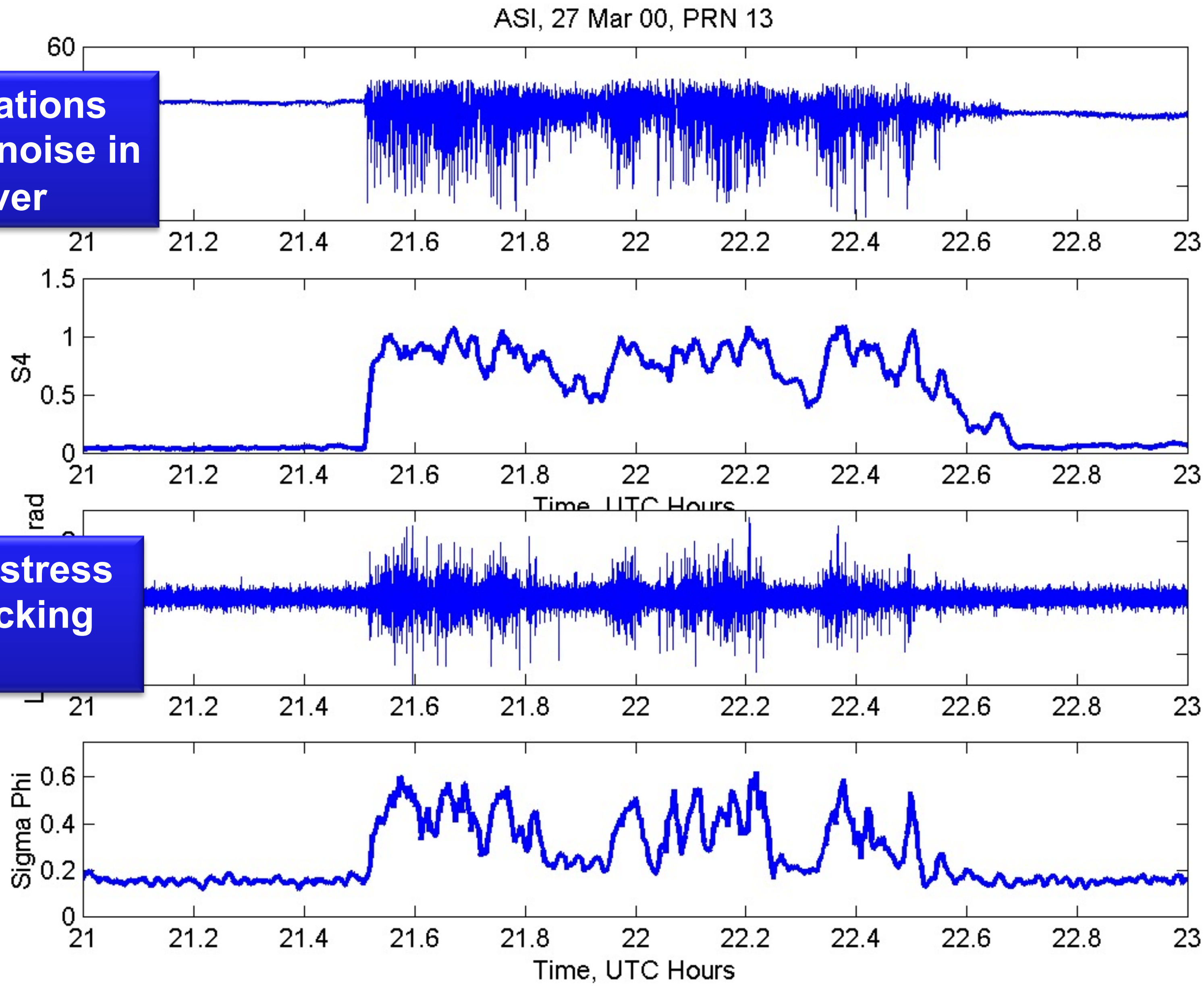
GPS Signal Fluctuations Caused by Ionospheric Scintillation

Intensity fluctuations reduce signal-to-noise in GNSS receiver

S4: normalized st. dev. of intensity

Phase variations stress GNSS signal tracking loops

σ_{ϕ} : st. dev. of phase

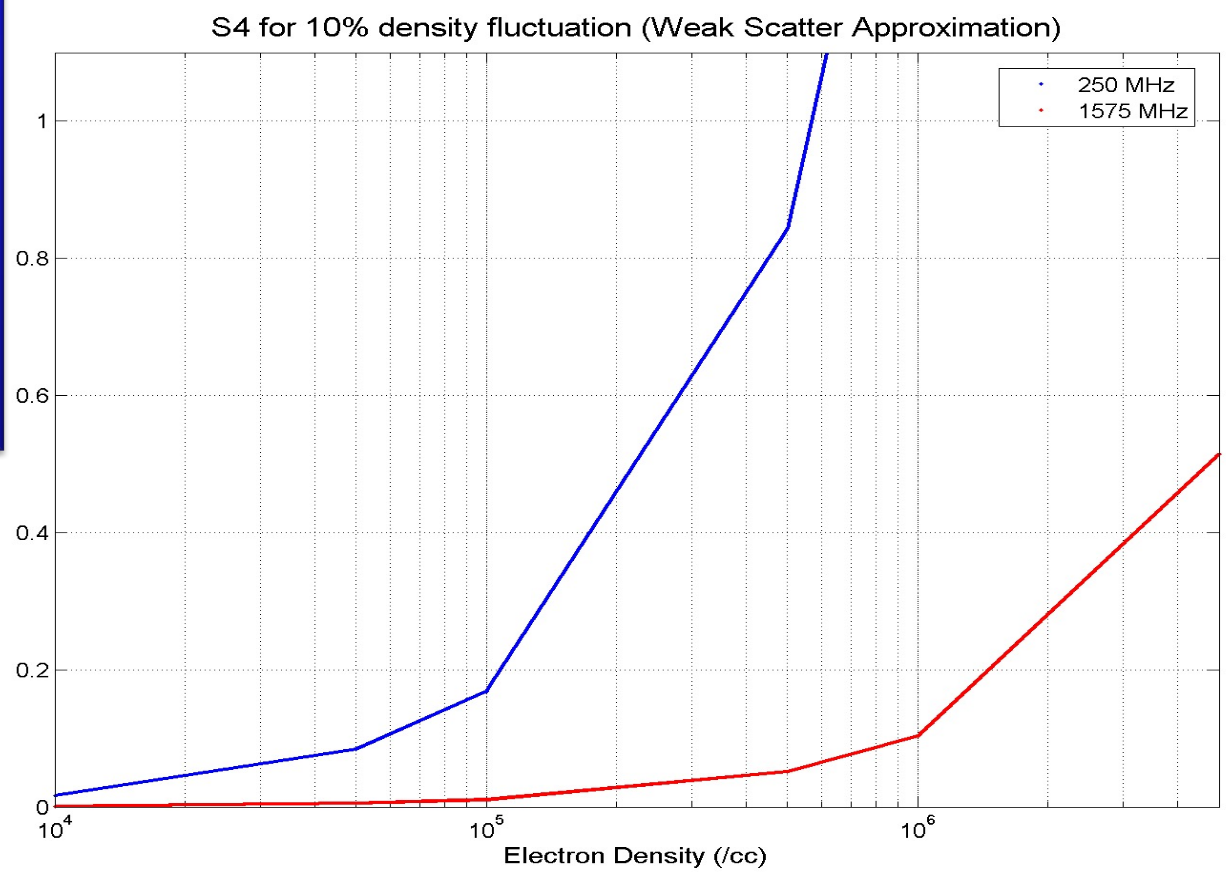


Effect of Electron Density on Scintillation

Scintillation requires two physical ingredients:

1. **Electron density**
2. **Small-Scale Irregularities**

- Significant relative density fluctuations will not cause scintillation if the background electron density is too low
- NmF2 must exceed ~10^5/cc for VHF scintillation, ~10^6/cc for GNSS (~50 TEC units)



$$N\sigma_{N/\Delta N} = S_4^{thresh}\left\{2\pi r_e^2 \lambda^2\, q_0 L \sec\theta \left(\frac{\lambda z_R \sec\theta}{4\pi}\right)\right\}^{-1/2}$$

Weak Scatter Approximation

(assumes fluctuation σ = 10%)

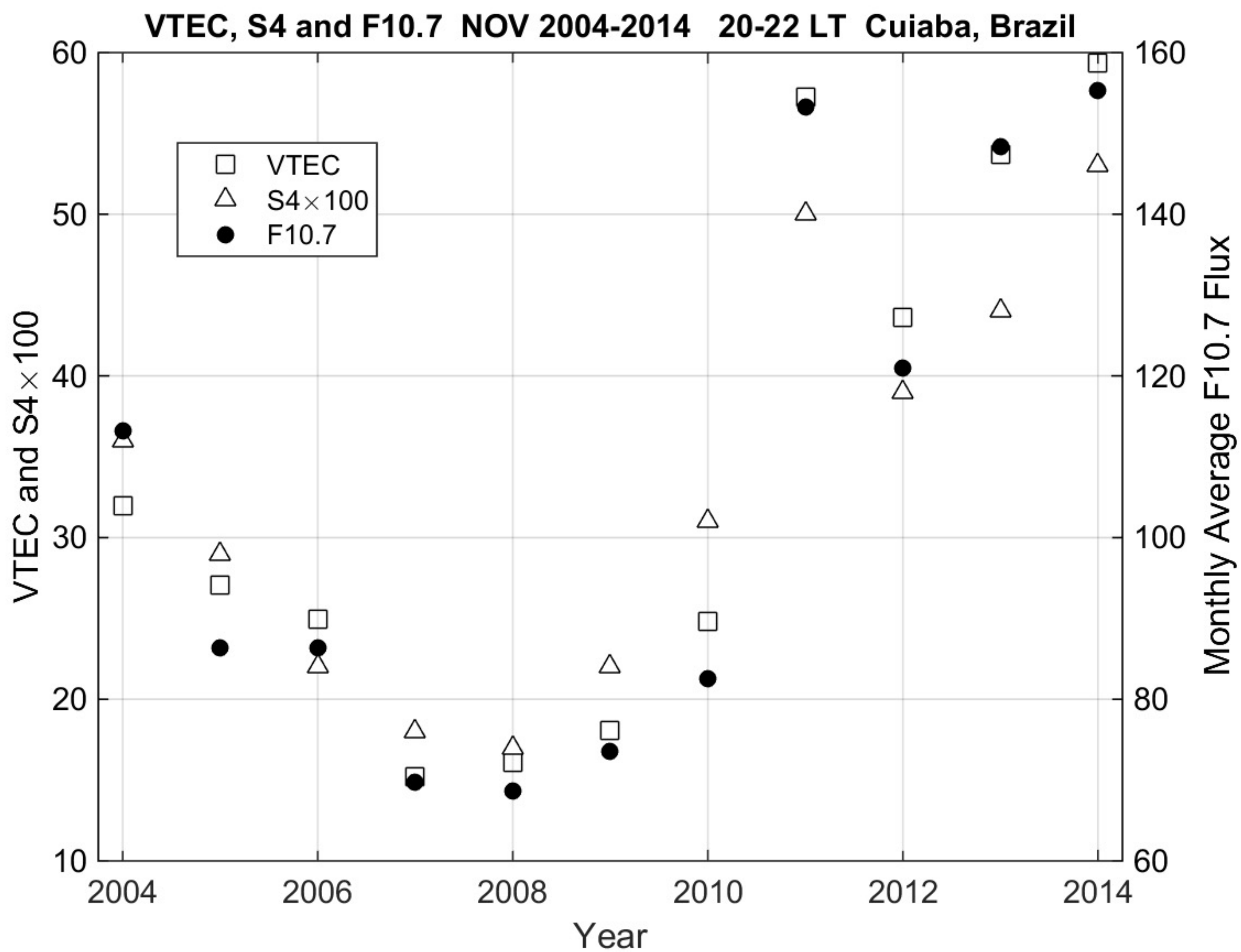
Implications for the Ionosphere & GNSS

Let's run some numbers…

- At L-band, $\delta\varphi \approx 5 \times TEC \text{ radians}$, so a phase changes of ~ π radians (condition for destructive interference) requires $\delta TEC \approx 0.6$ TECu.
- But the variations must occur over limited spatial scale, the Fresnel zone, $F_r = \sqrt{2\lambda z}$, ~ 500 meters for L1 and typical iono parameters

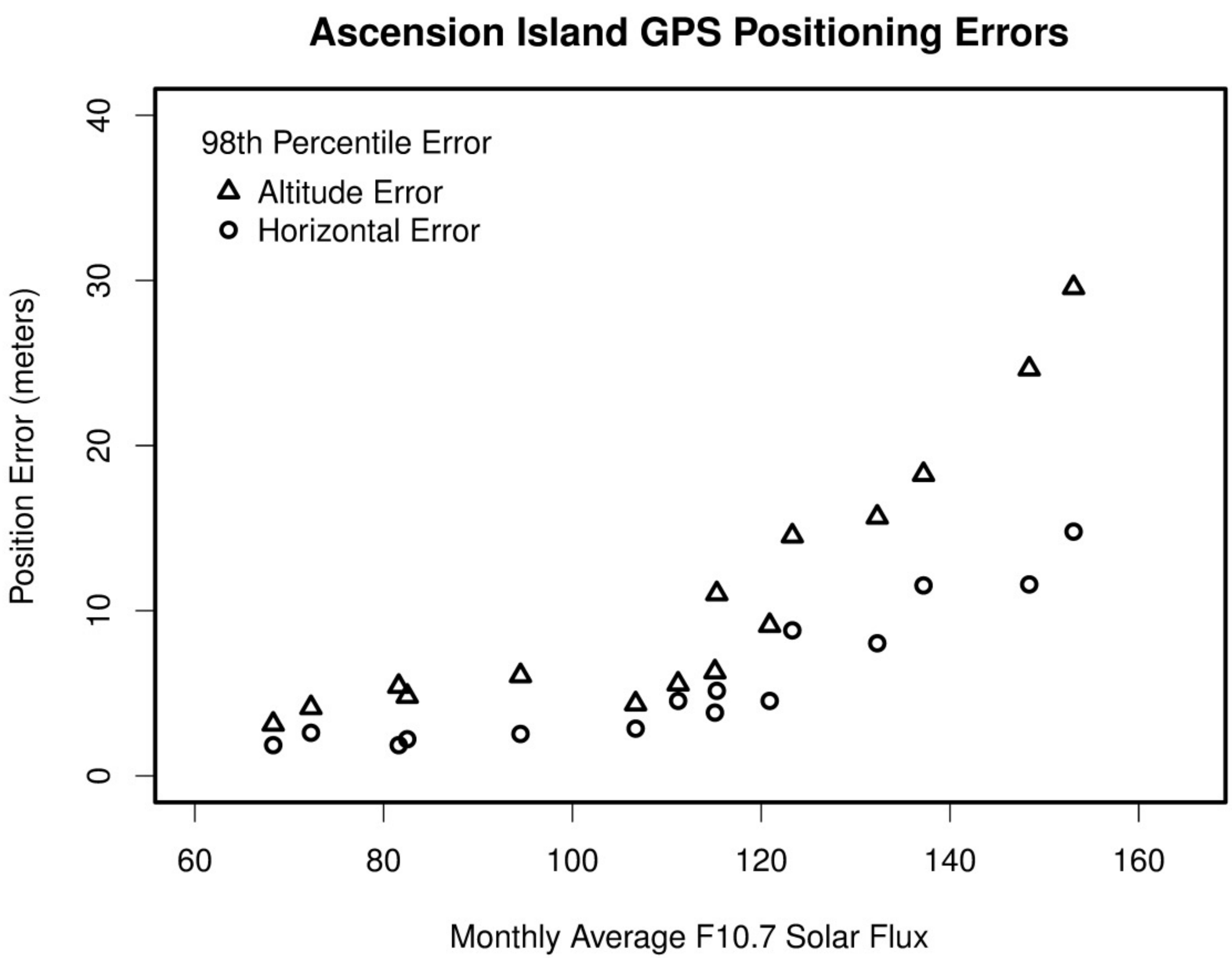
- Solar max TEC ~ 50-100
  - Small relative density fluctuations required (1-2%)
- Solar min TEC ~ 1-5 (nighttime)
  - Large relative density fluctuations required (10-50%)
- Consistent with expectations, GNSS scintillations are generally weak during solar minimum
- Scintillation impacts on GNSS are limited to solar max periods (3-4 years around peak)

Solar Flux, Density & S4



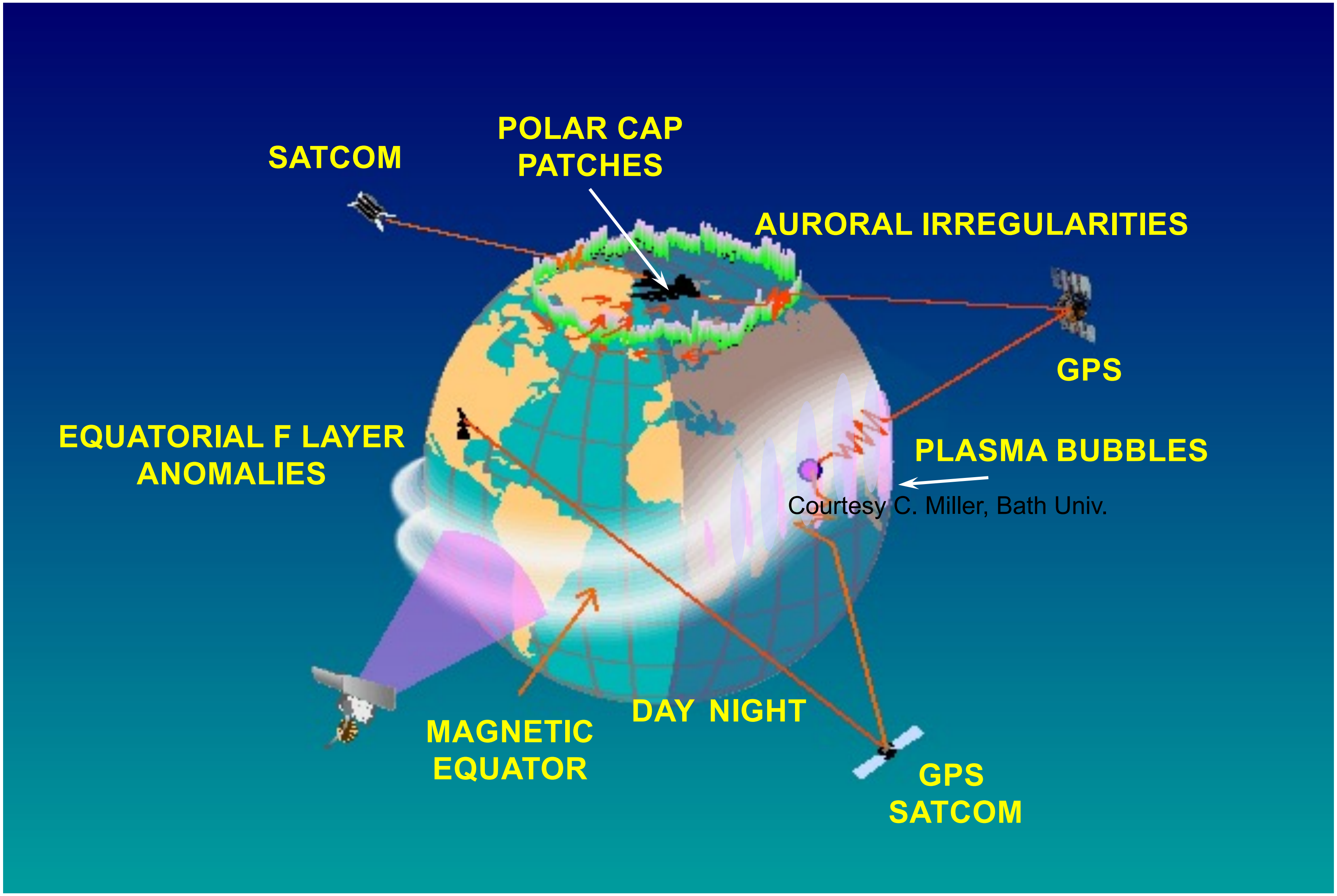
Solar flux determines electron density which determines S4

Solar Flux & Positioning Errors

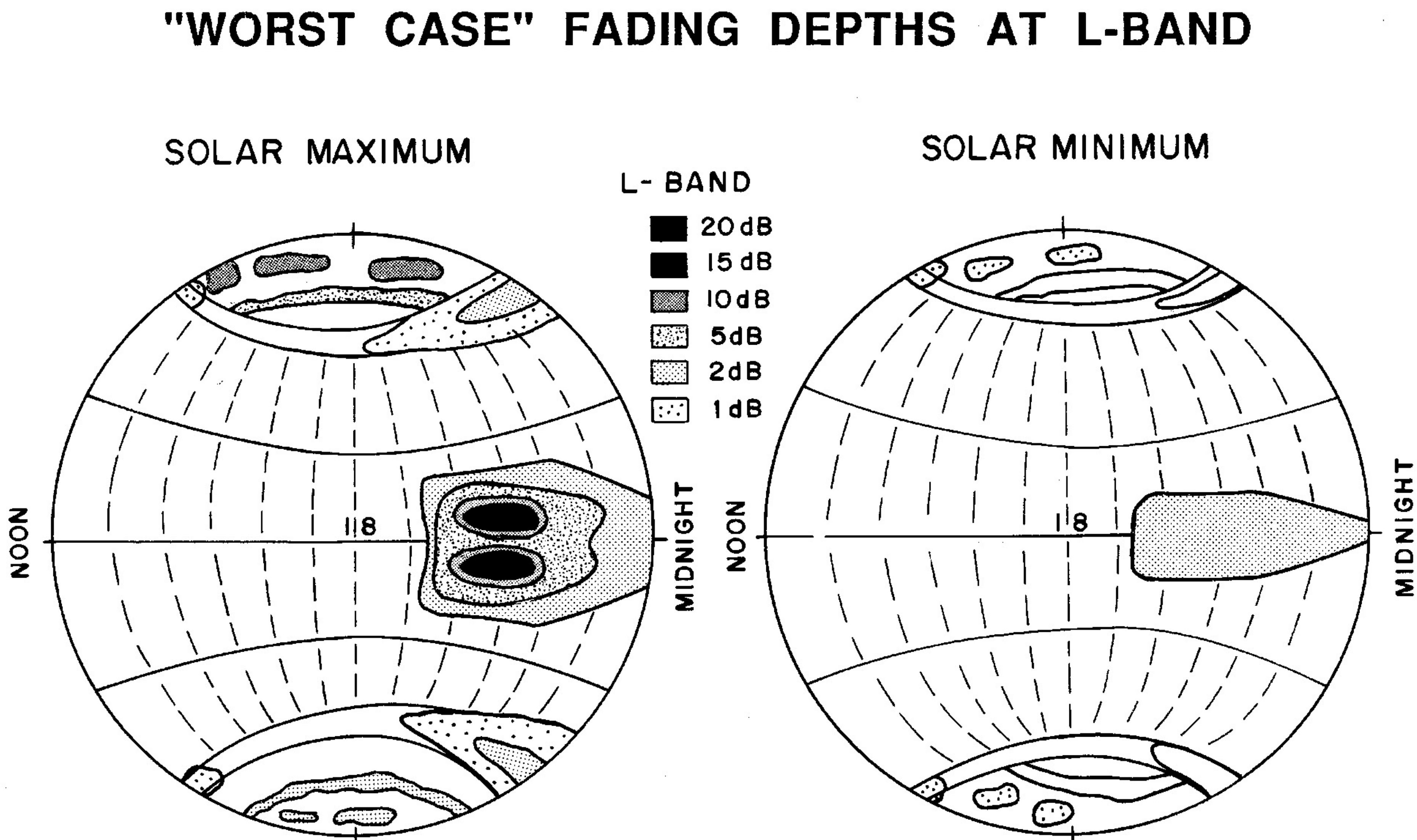


Solar flux controls S4 which controls impact on GNSS performance

Disturbed Ionospheric Regions



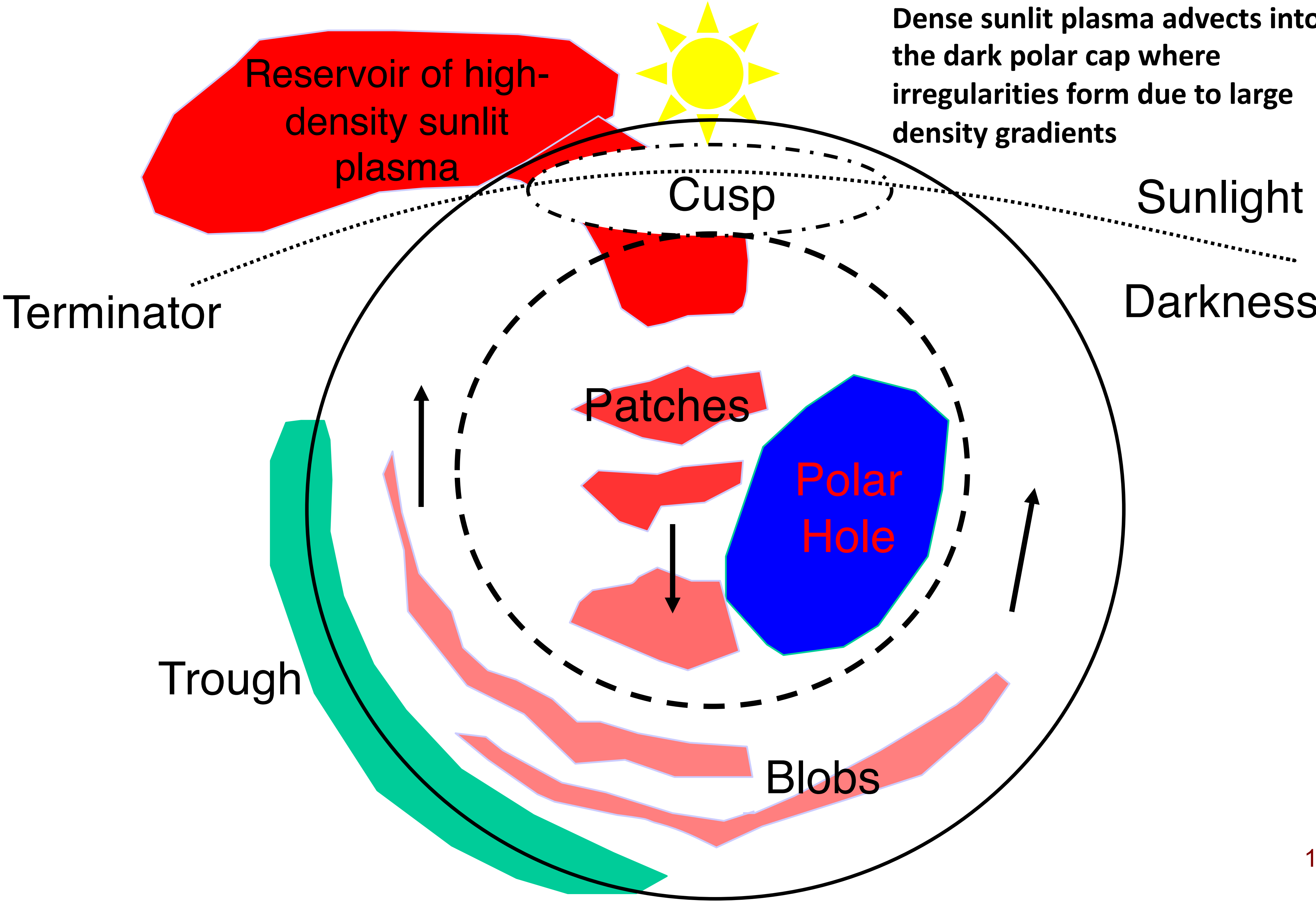
Global Morphology



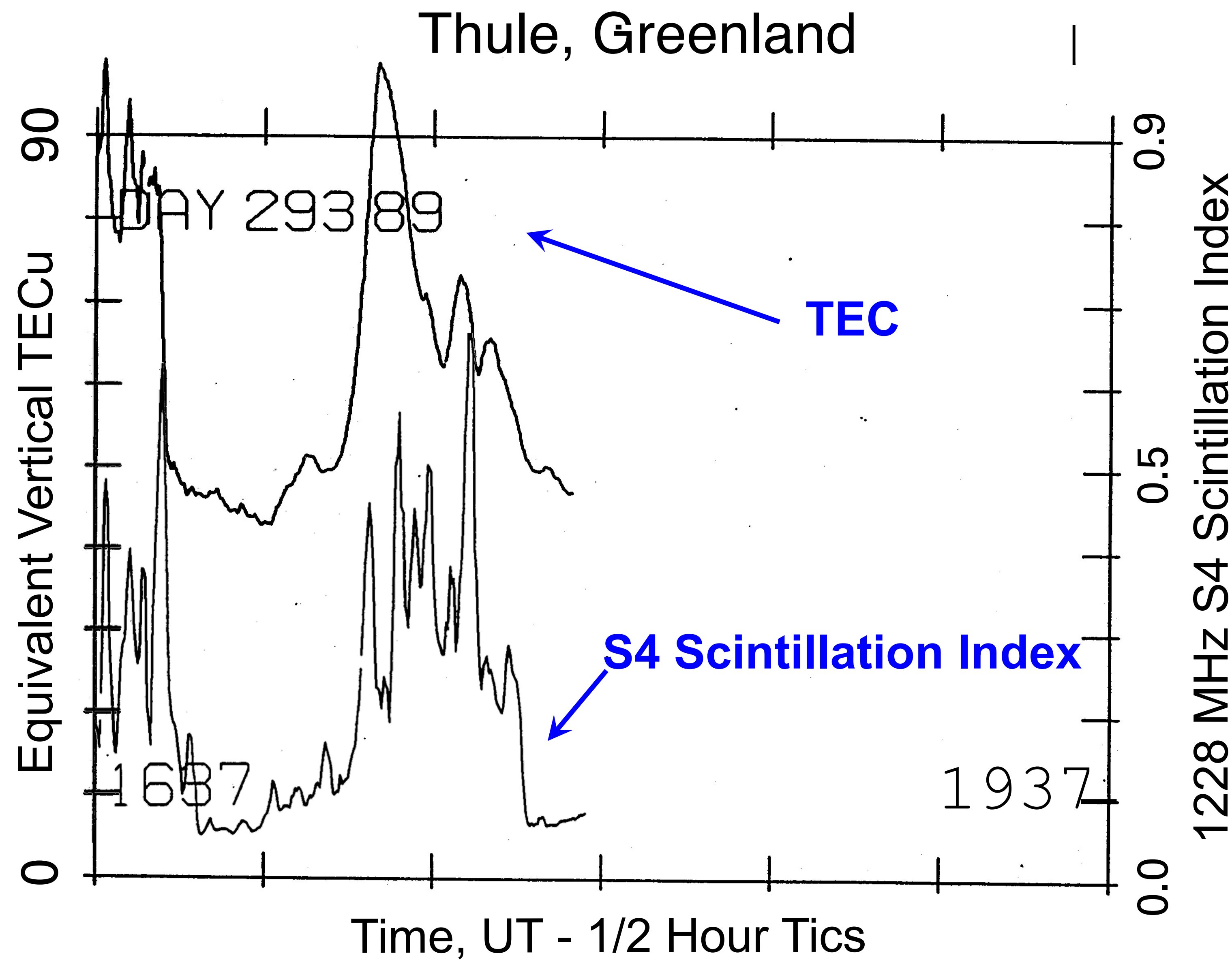
[After Basu, et al.]

Polar Ionosphere Density Regimes (Winter, Bz < 0)

Dense sunlit plasma advects into the dark polar cap where irregularities form due to large density gradients



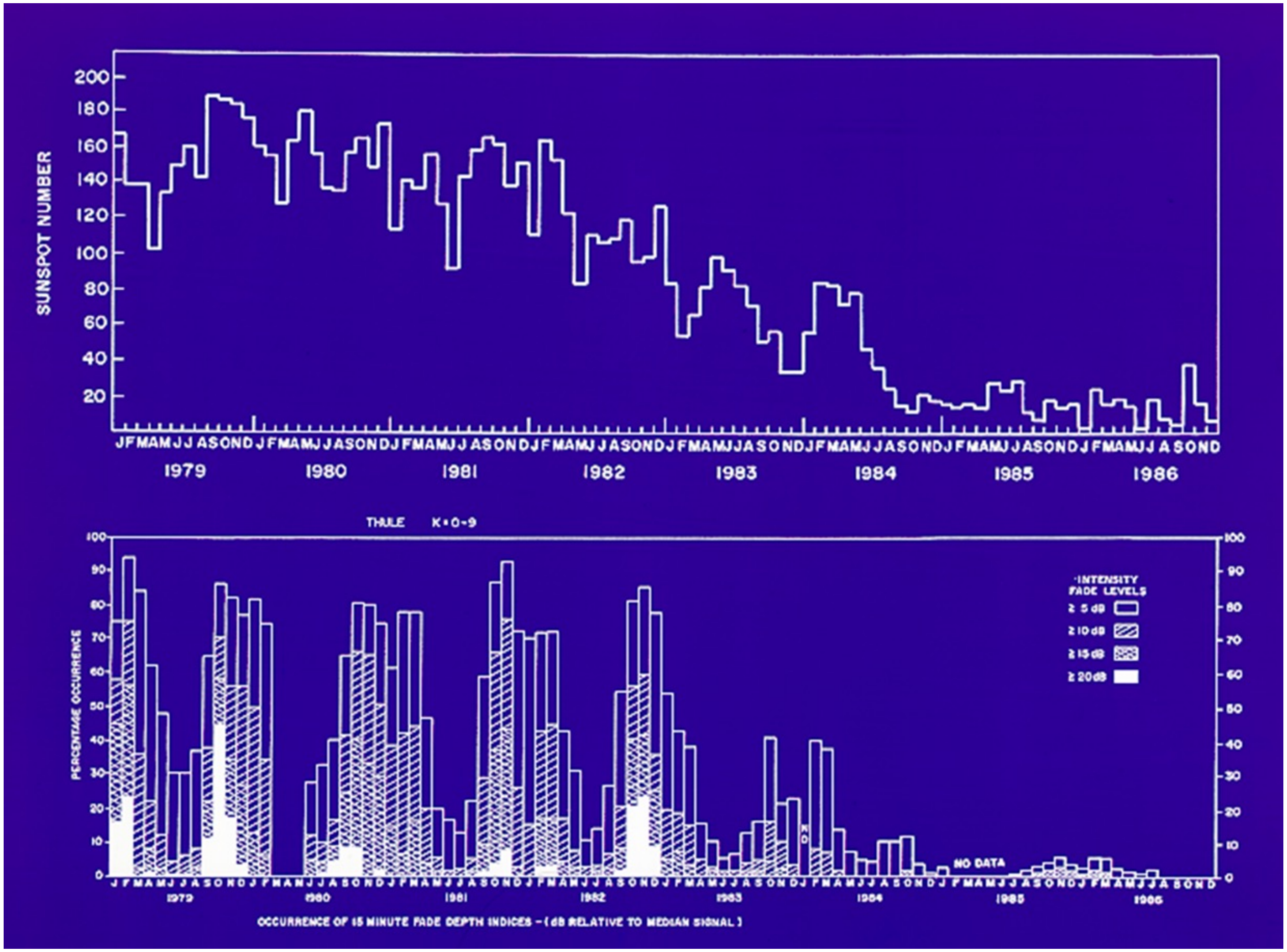
TEC Fluctuations and Scintillation during Patch Events



Bishop, et al.

Polar Cap Scintillation
Thule, Greenland

Seasonal and solar cycle dependence of scintillation from polar cap patches

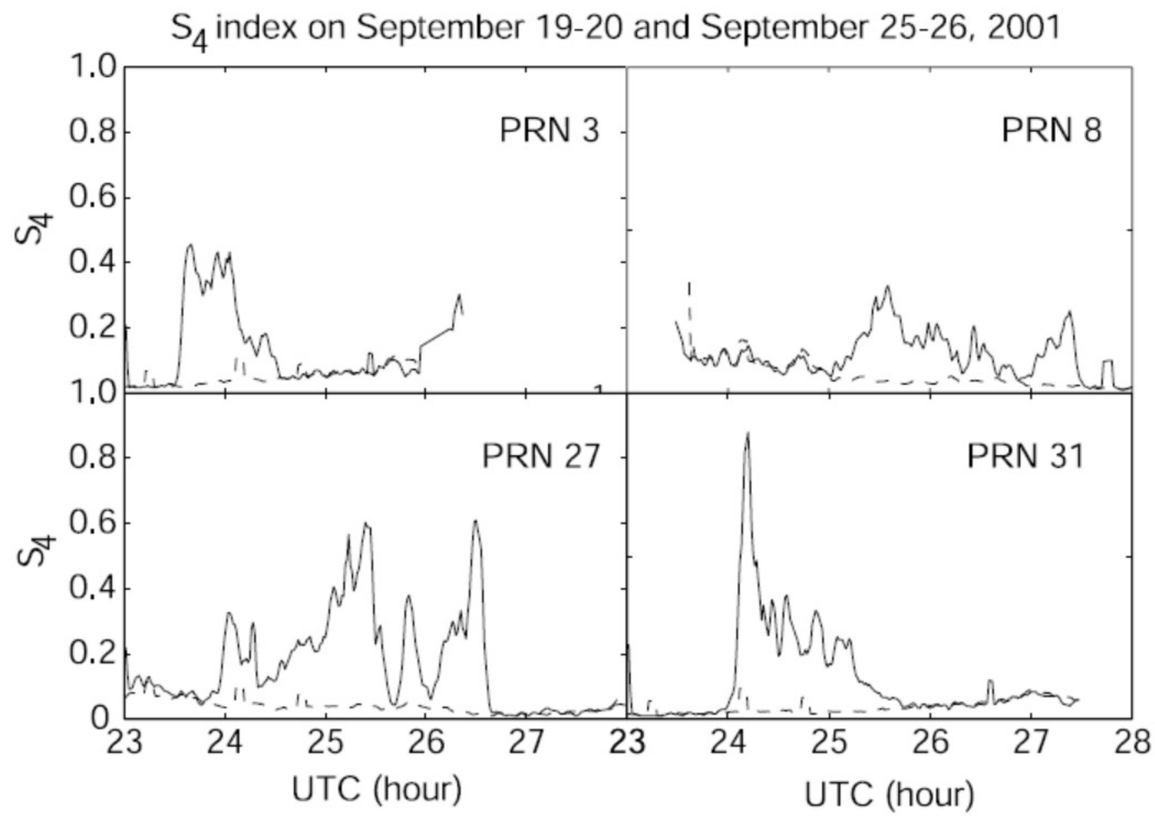


Why doesn’t scintillation occur during periods of low solar flux?
Why doesn’t it occur during sunlit months?

Mid-Latitude Scintillations

Under what conditions does the mid-latitude ionosphere develop small-scale structure leading to scintillation?

- Storm-time electric fields cause widespread, dynamic changes in the mid-latitude ionosphere
- Strong irregularities form where density enhancements and instabilities coincide
- Details are a topic of active research, but multiple mechanisms are involved



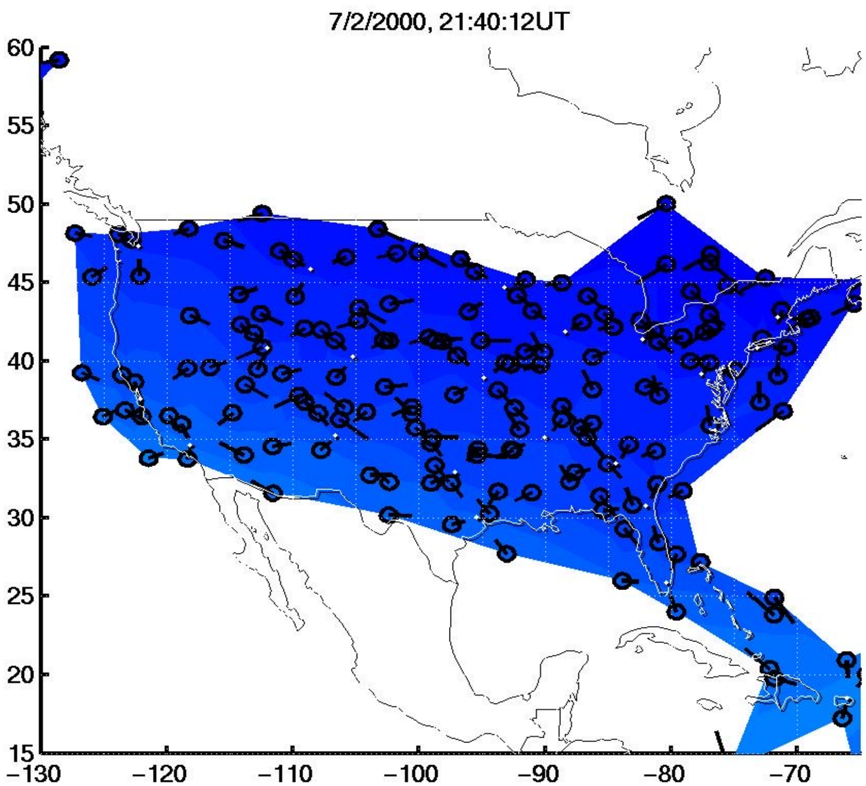
L1 S4 observations from Ithaca, NY

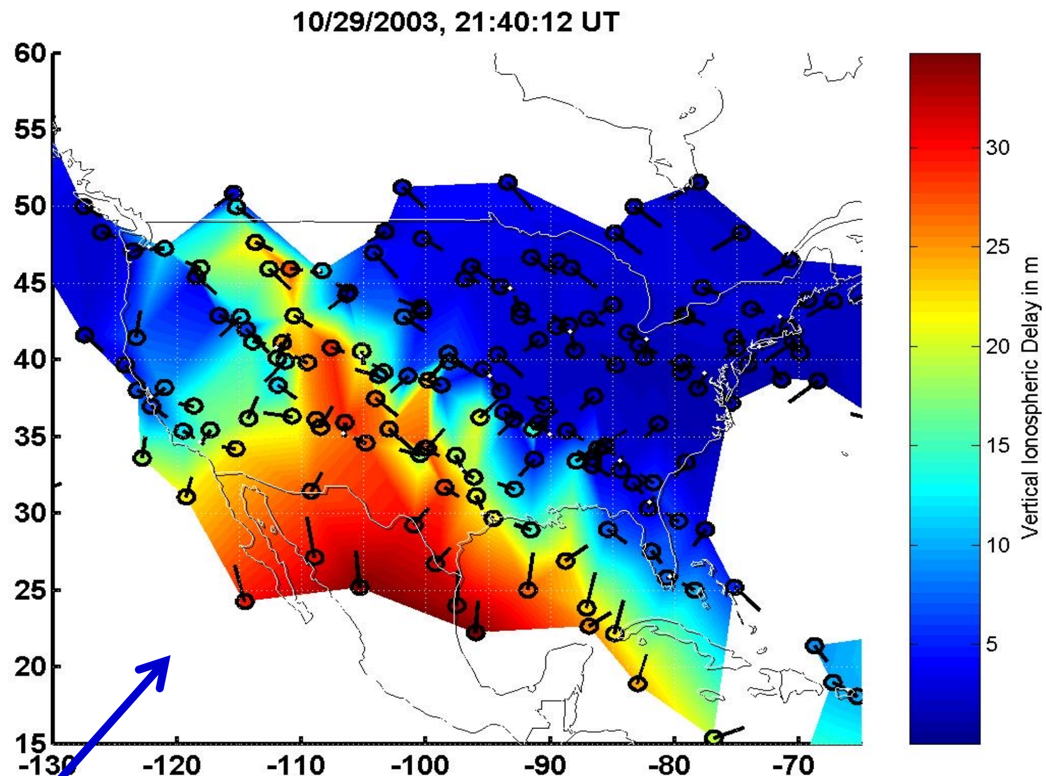
(Ledvina et al., 2002)

Quiet versus Disturbed Ionosphere: Storm-time Enhanced Density Events

Mid-latitude Gradients & Structure

WAAS Reference Station Measurements





Storm-time Enhanced Density (SED) [Foster 1993, Foster et al., 2002]

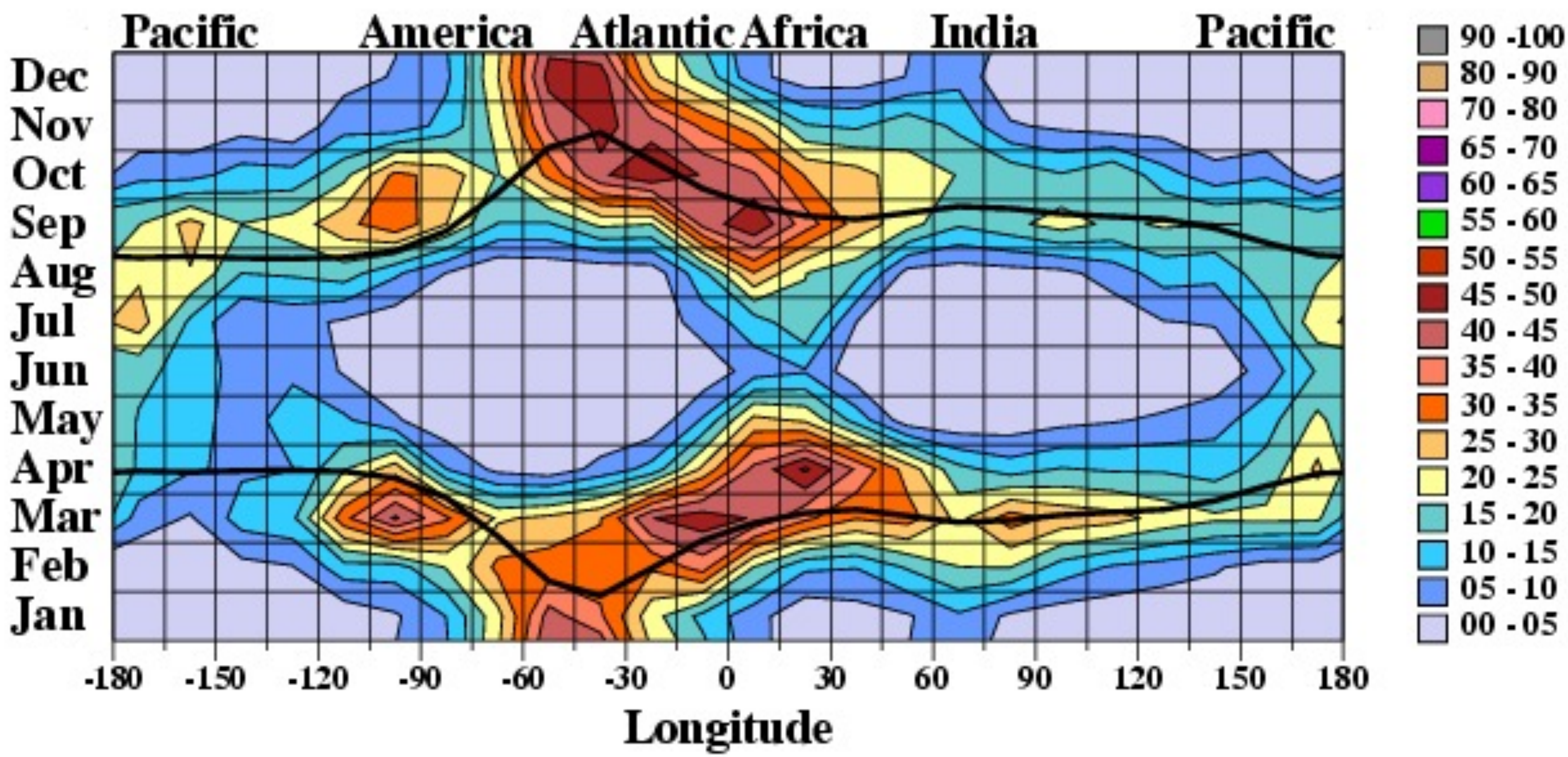
Results in loss of vertical guidance availability

Figures courtesy of Seebany Datta-Barua

What About the Equator?

In situ irregularities detection statistics
DMSP satellite 800 km circular polar orbit, 1989

800 km Occurrence Climatology



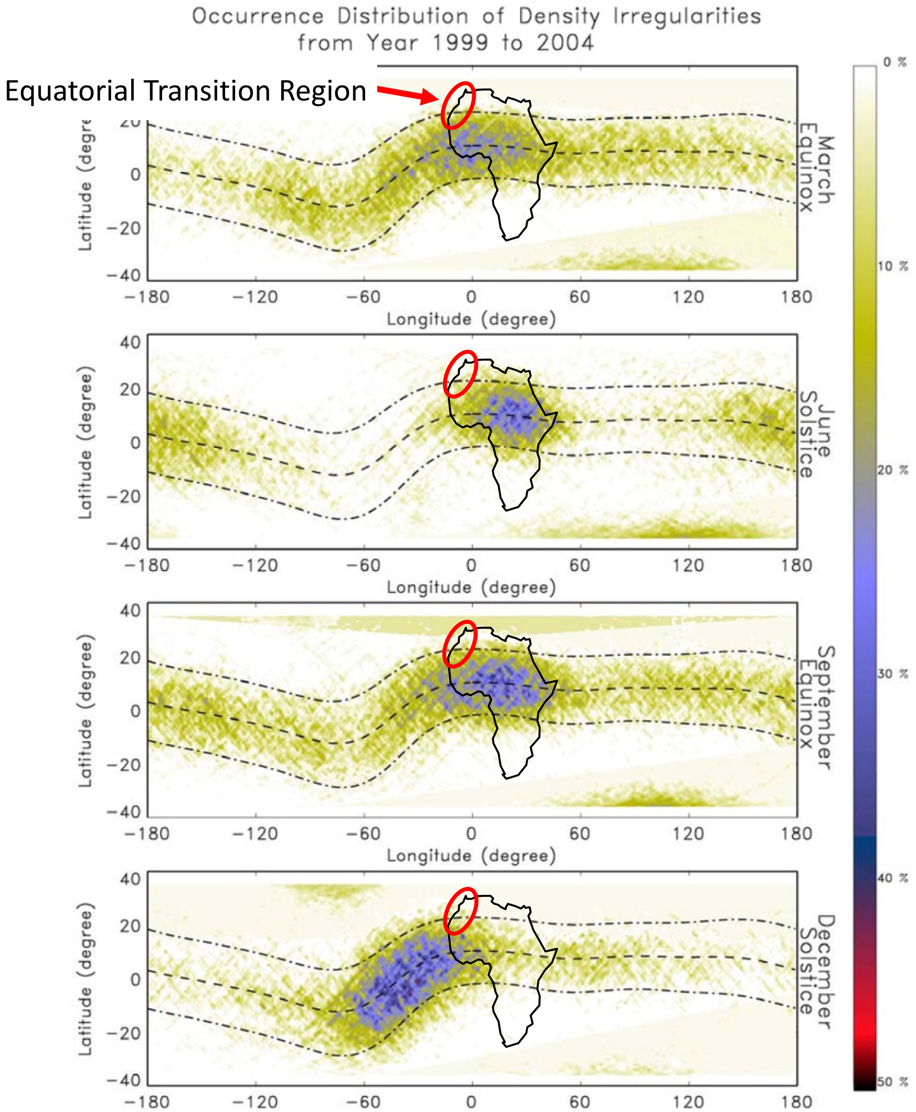
From Burke & Huang [2004]

Scintillation Activity over Africa

Low-latitude scintillation affects nearly 50% of the earth's surface.

- ROCSAT observed irregularities above Africa virtually year round.
- C/NOFS saw a similar integrated maximum in activity over Africa.
- The reasons for this are still under investigation.
- The post-sunset scintillation is a regular feature of the low-latitude ionosphere over Africa and space-based radio frequency systems must be prepared to deal with it.
- Morocco is an exciting place to make observations: it is ideal for monitoring the day-to-day variability of the anomaly region which is not well characterized or understood!

ROCSAT (600 km)

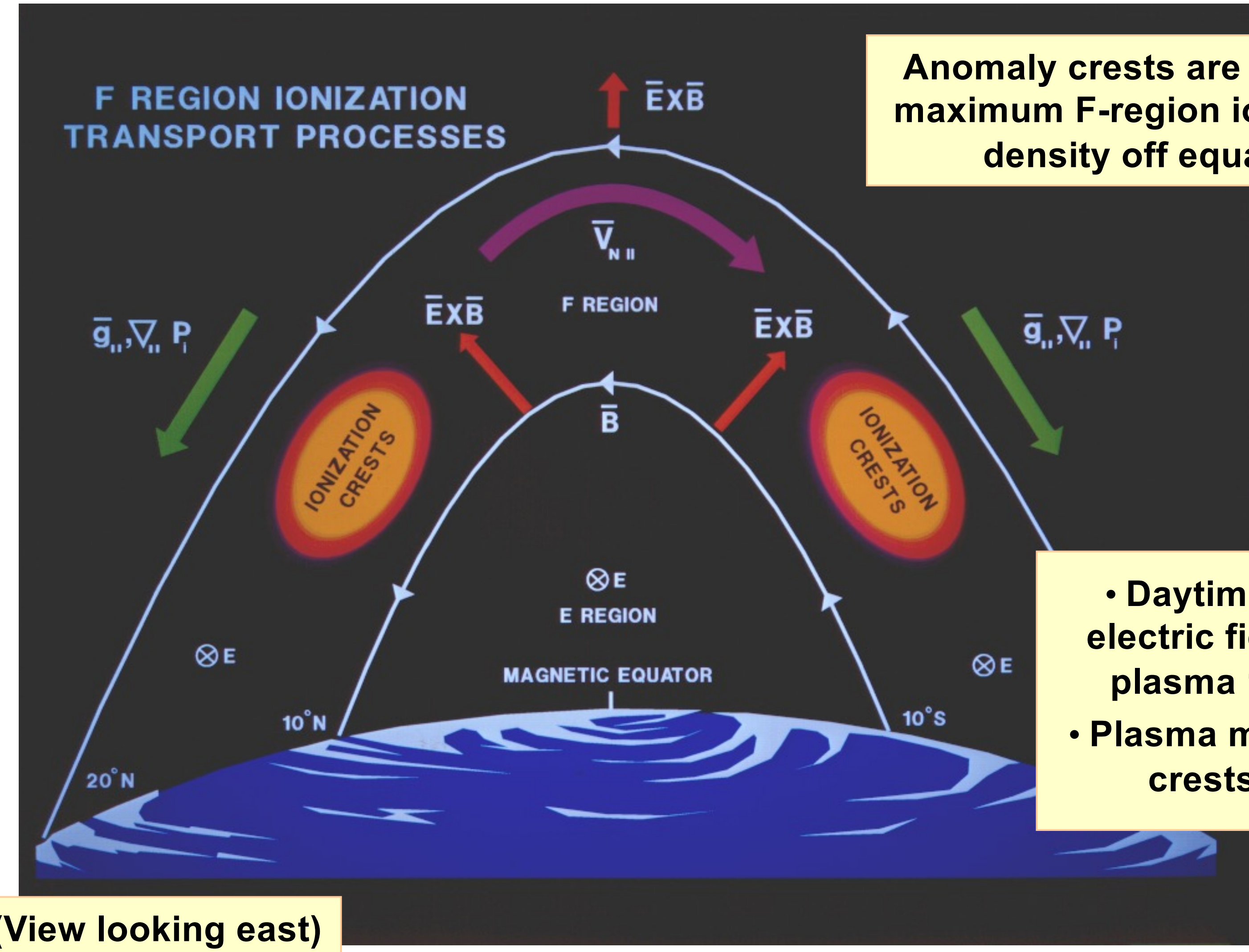


Adapted from S.Y Su, 2005

What Are Equatorial Dynamics?

Formation of Anomaly Region

- Presence of anomaly crests strengthens off-equator scintillations
- State of anomaly formation is indicative of equatorial dynamics



Anomaly crests are areas of maximum F-region ionization density off equator

- Daytime eastward electric field (E) drives plasma "up" (**E × B**)
- Plasma moves toward crests ($g^{\parallel}$, $\nabla^{\parallel}P^{\parallel}$)

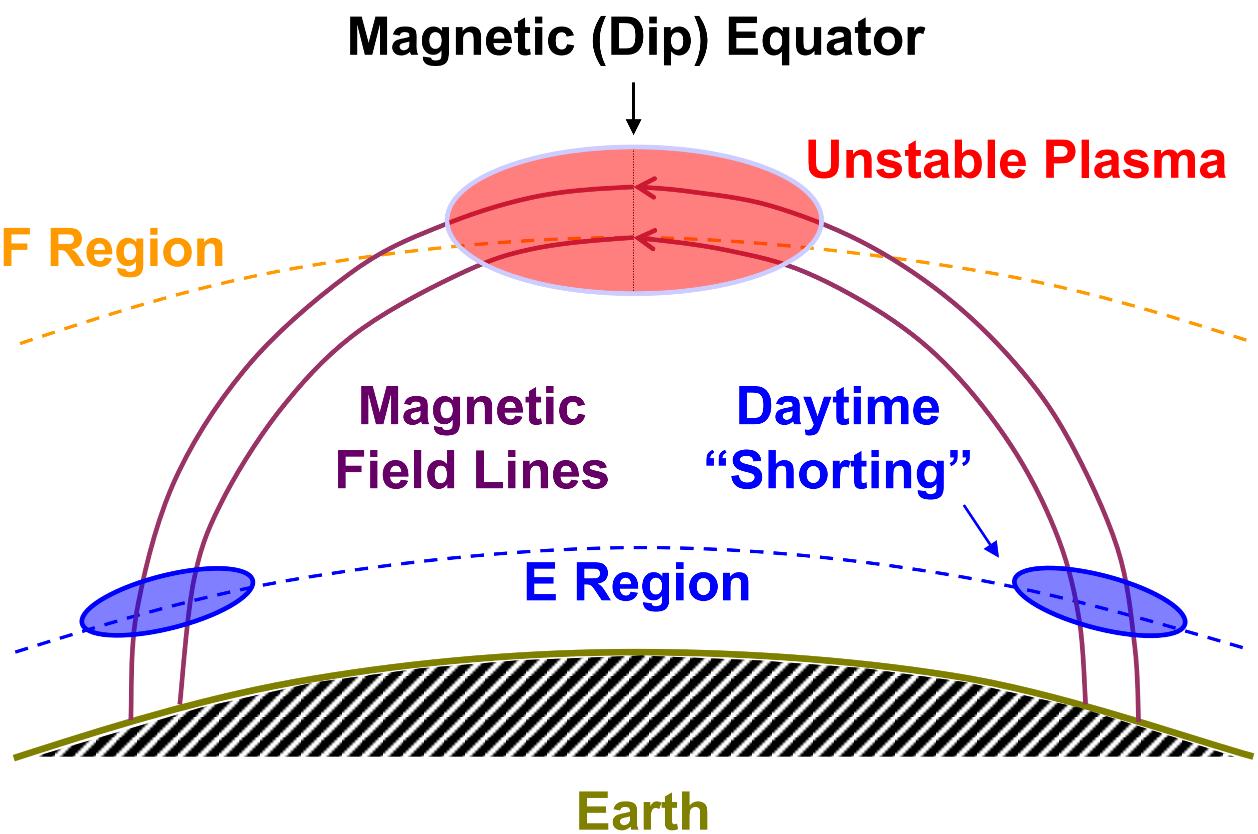
(View looking east)

Why Do Disturbances Form?

Unique Equatorial Magnetic Field Geometry

Equatorial scintillation occurs because plasma disturbances form readily with horizontal magnetic field

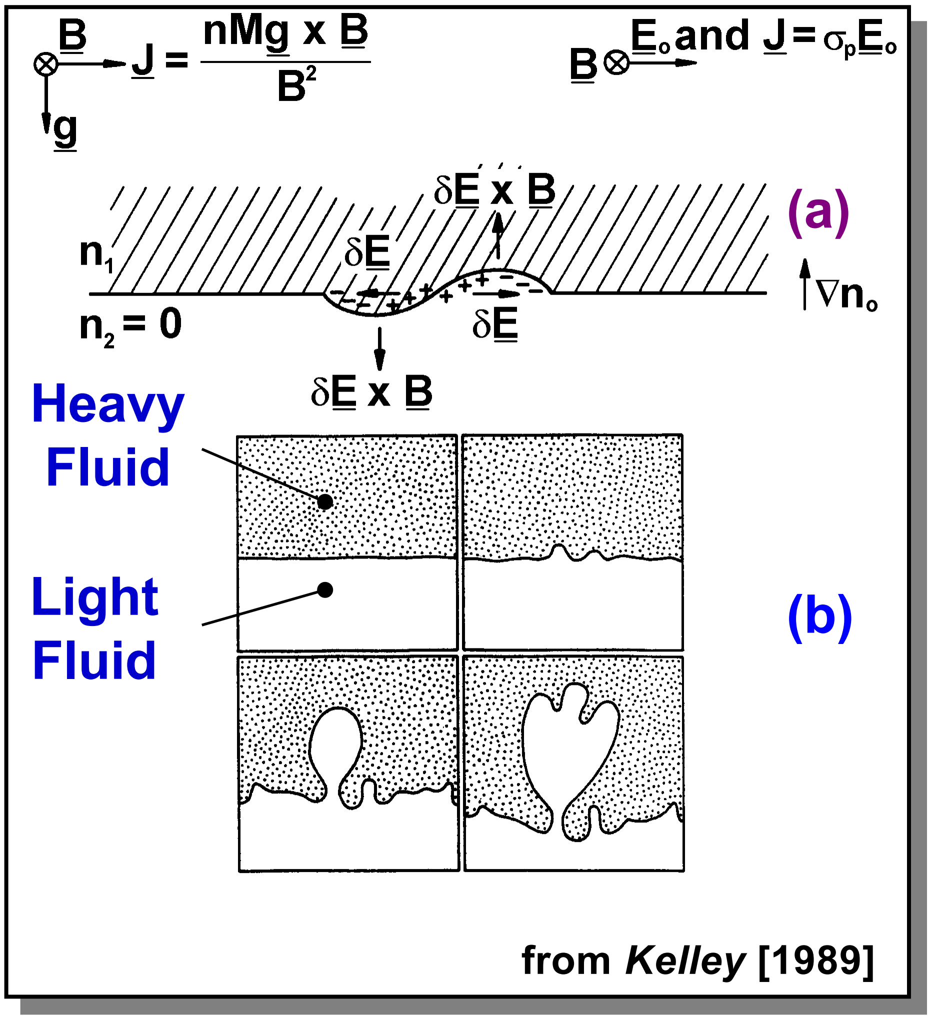
- Plasma moves easily along field lines, which act as conductors
- Horizontal field lines support plasma against gravity– unstable configuration
- E-region "shorts out" electrodynamic instability during the day



What Is Instability Process?

Basic Plasma Instability

View along bottomside of ionosphere (E-W section, looking N from equator)



from *Kelley* [1989]

Plasma supported by horizontal field lines against gravity is unstable

- (a) Bottomside unstable to perturbations (density gradient against gravity)
- (b) Analogy with fluid Rayleigh-Taylor instability
- Perturbations start at large scales (100s km)
- Cascade to smaller scales (200 km to 30 cm)

3D Model Realizations of Bubbles

T. Yokoyama, 2017

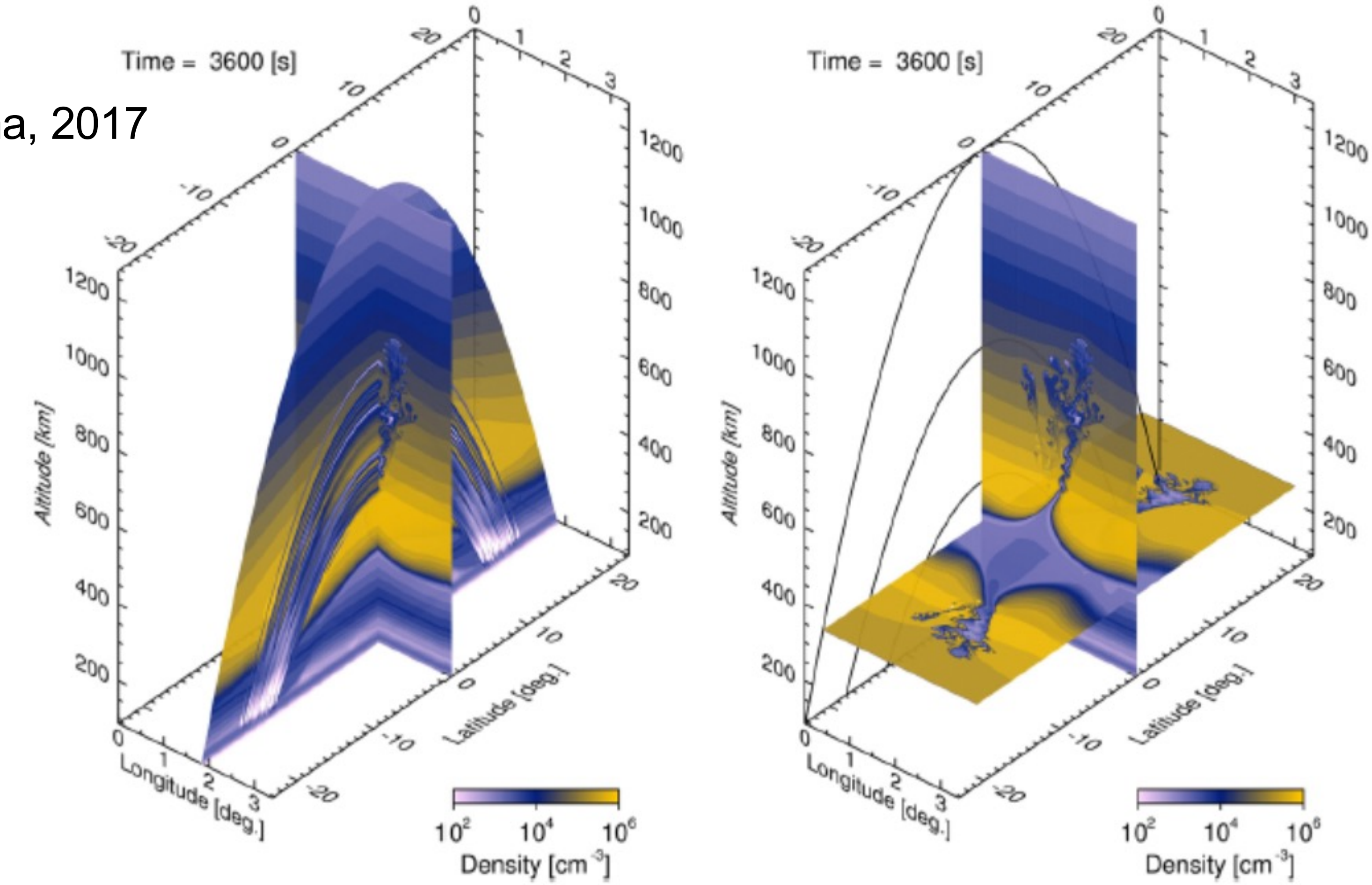
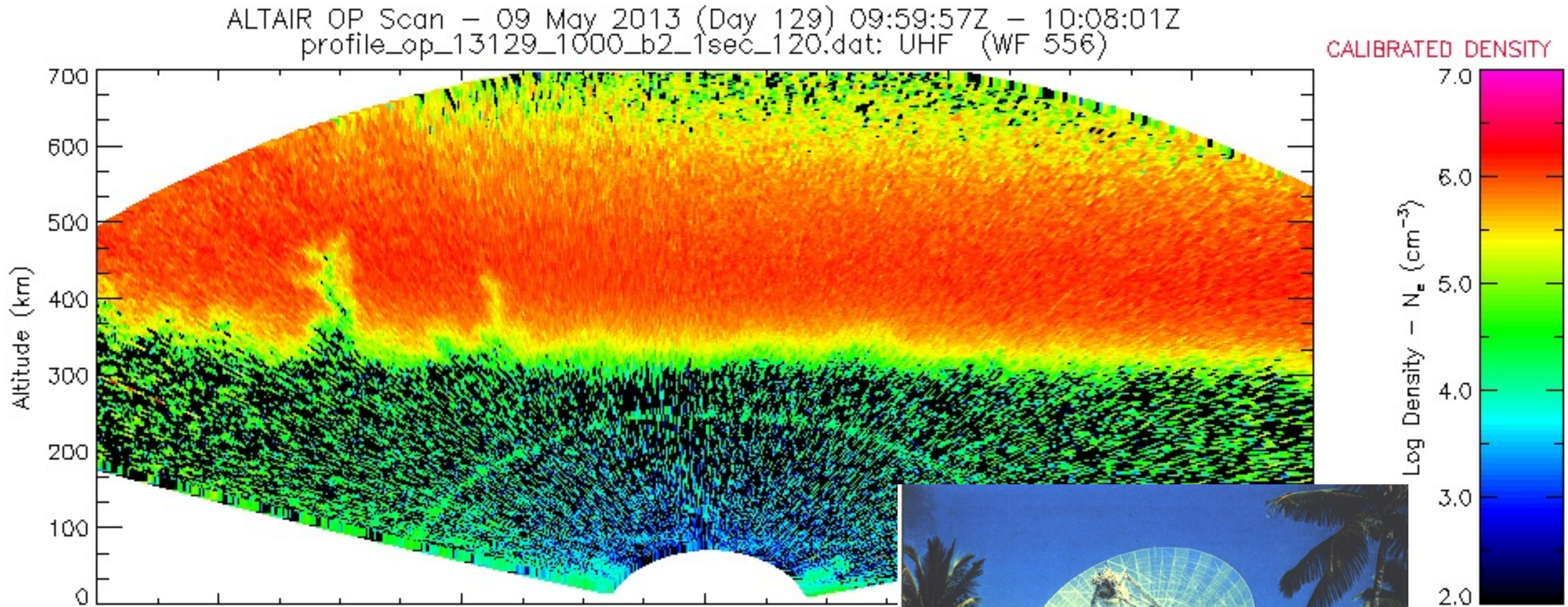


Fig. 1 Perspective view of the EPB simulation environment. The left frame shows the central meridian plane. The right frame shows the structure in two orthogonal slice planes

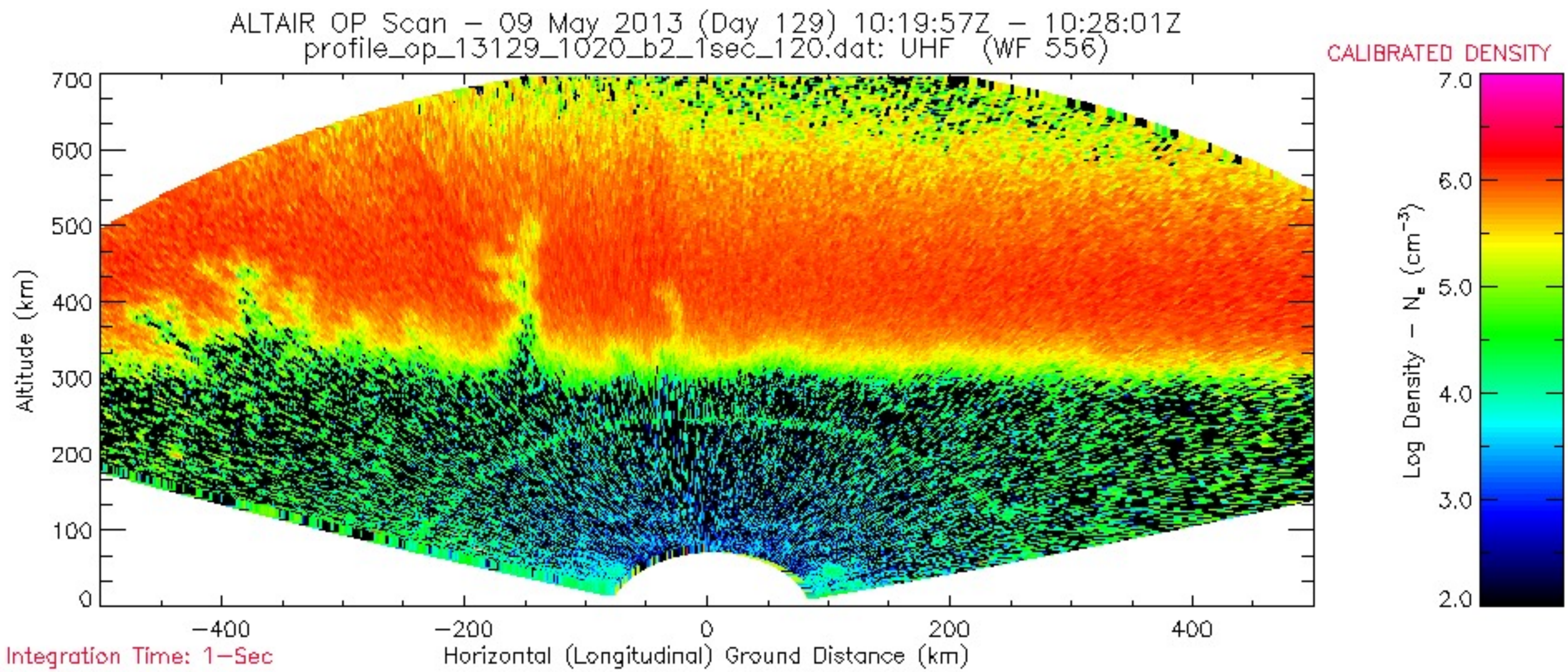
- Full fluid treatment simulations at scintillation-scale spatial resolution (~500 m)

10:00 UT to 10:08 UT

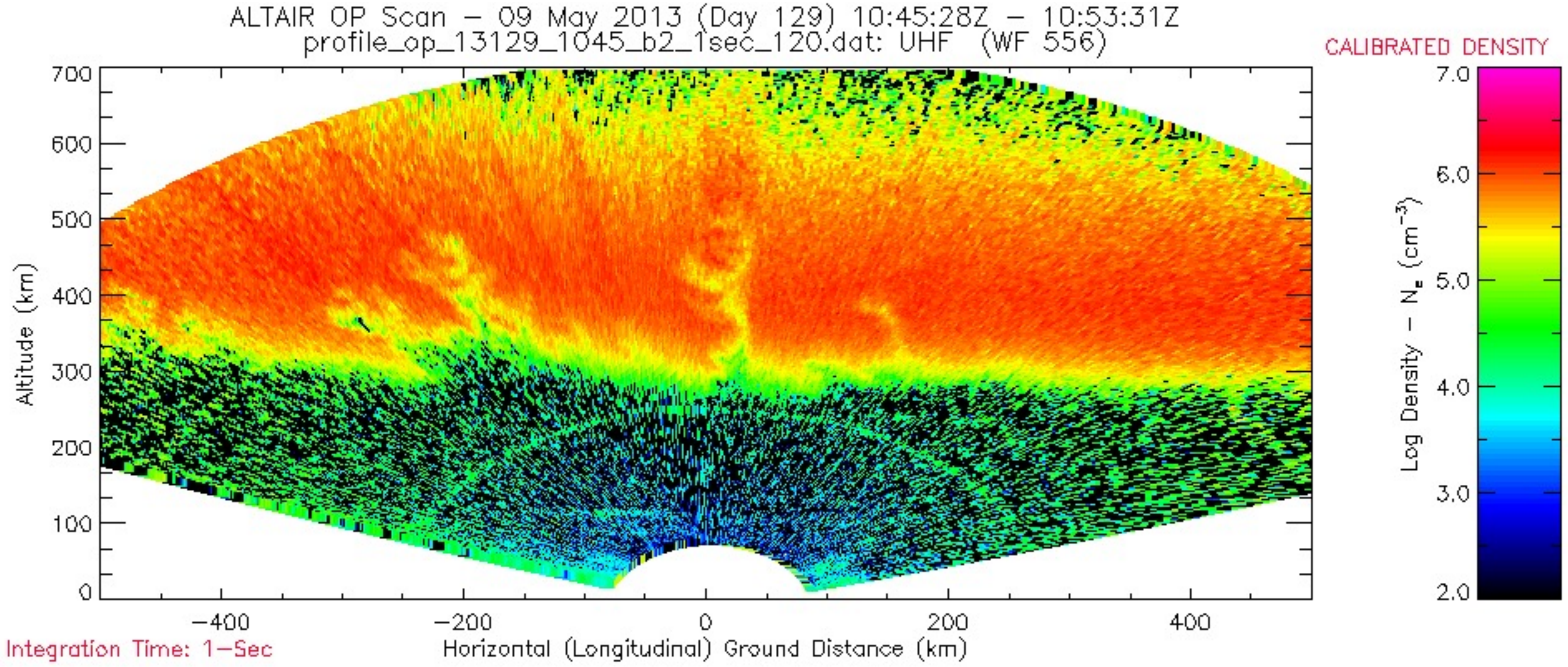


ALTAIR VHF/UHF Radar

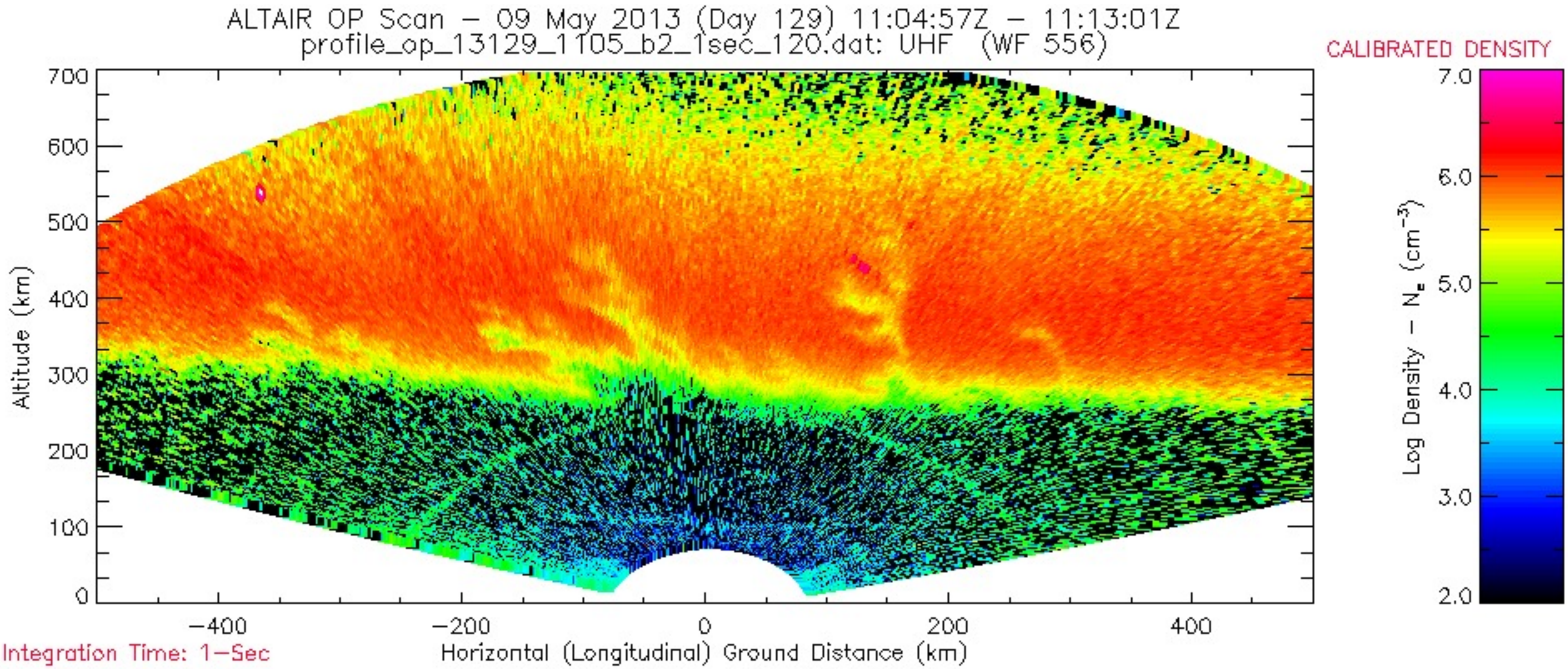
10:20 UT to 10:28 UT



10:45 UT to 10:53 UT

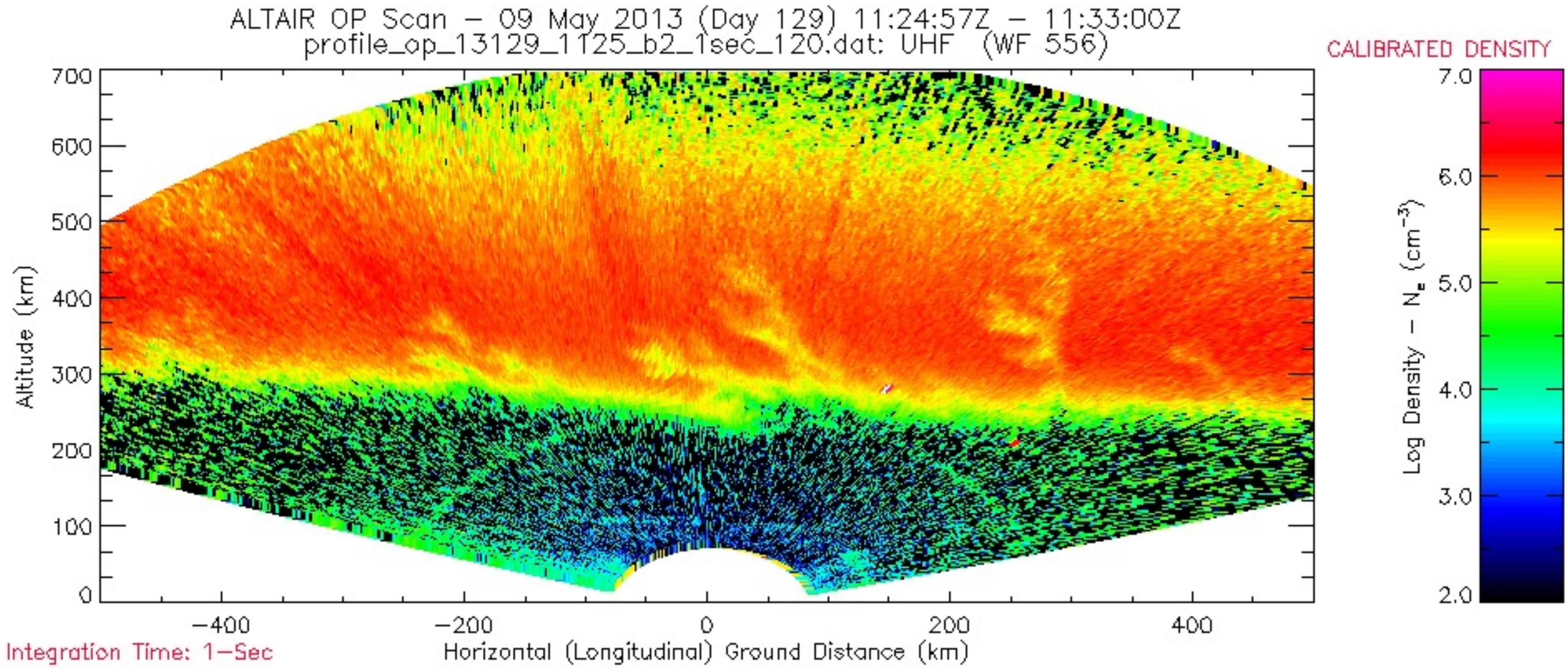


11:05 UT to 11:13 UT



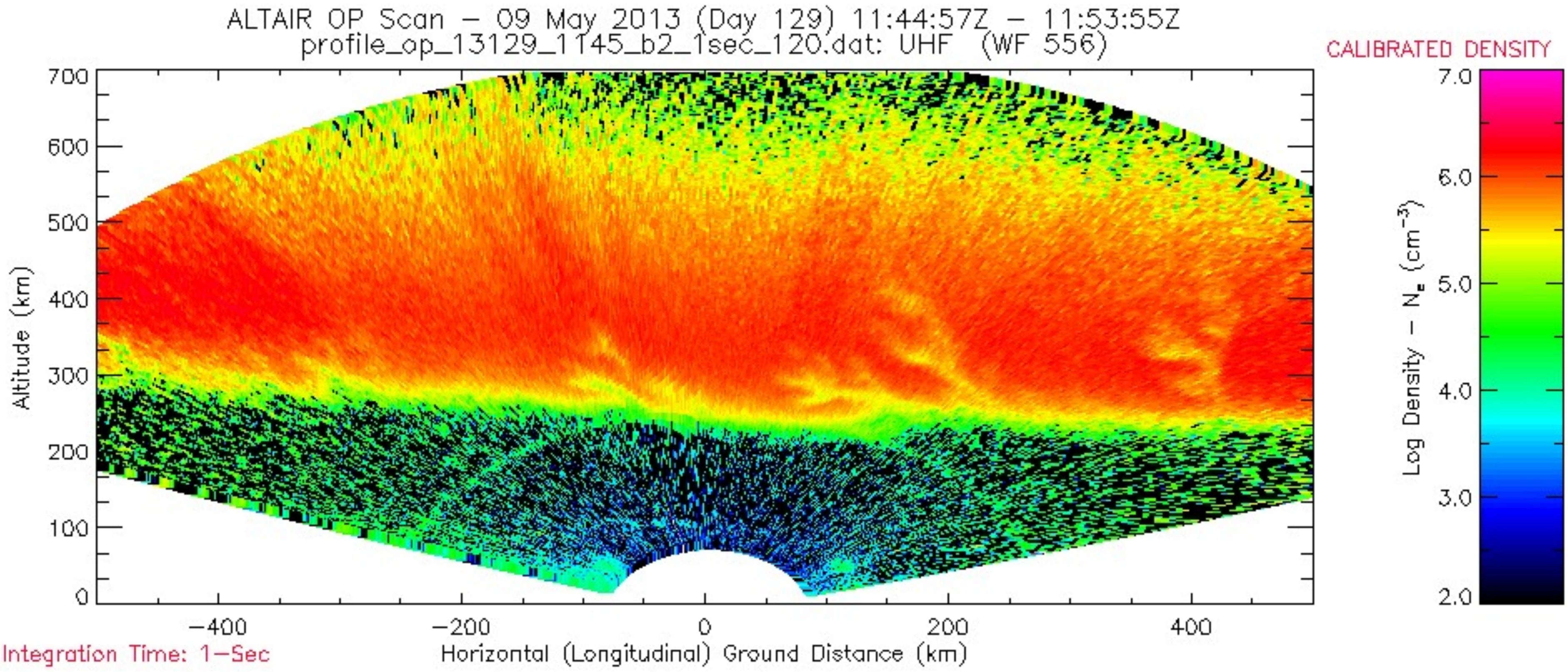
Off-Perp Incoherent Scatter Scans

11:25 UT to 11:33 UT

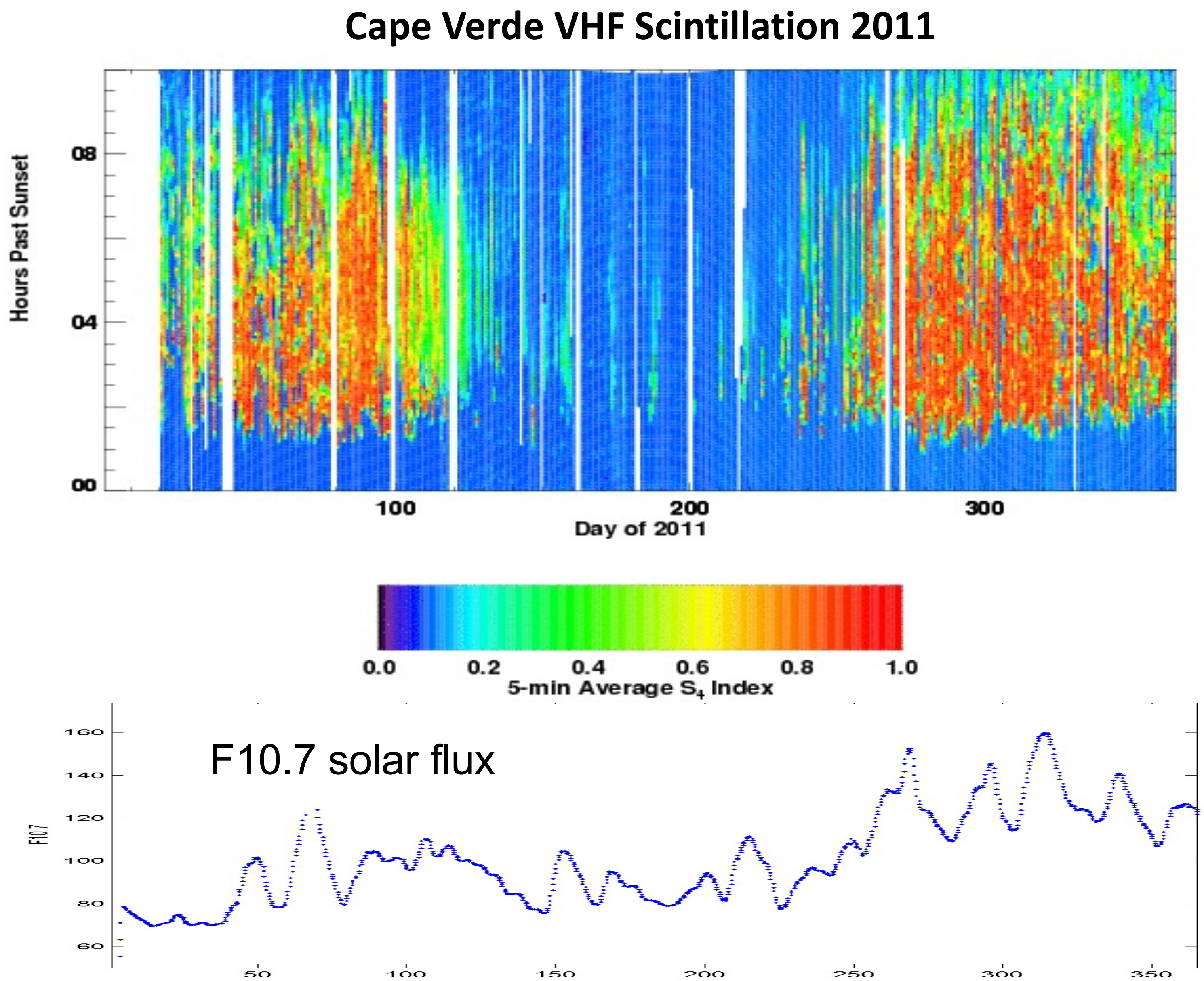


Off-Perp Incoherent Scatter Scans

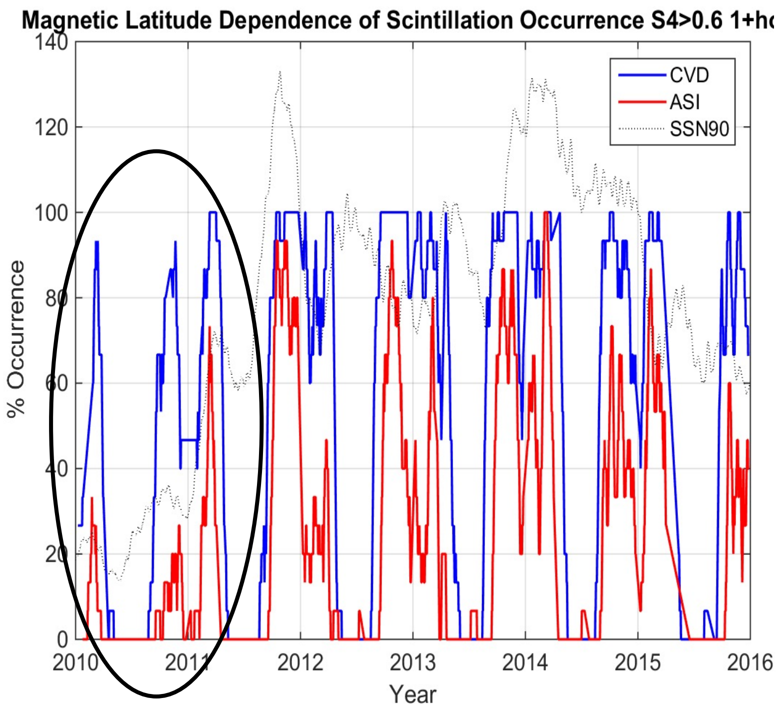
11:45 UT to 11:53 UT



Equatorial Scintillation Activity: West Africa

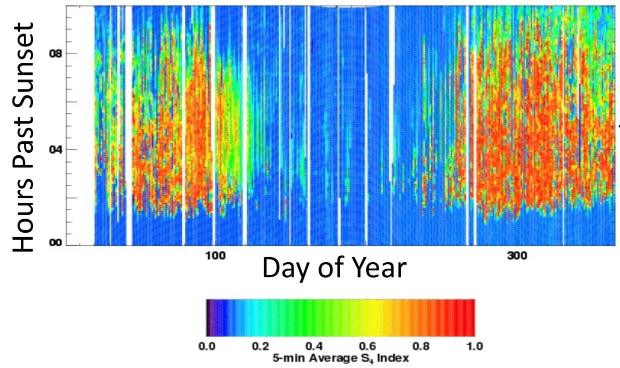


Relative Scintillation Occurrence by Latitude: Observations

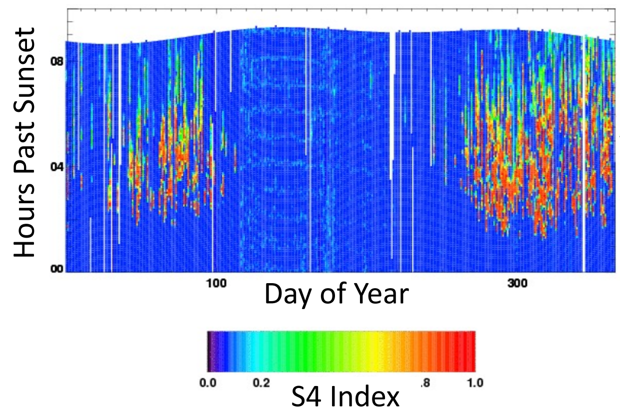


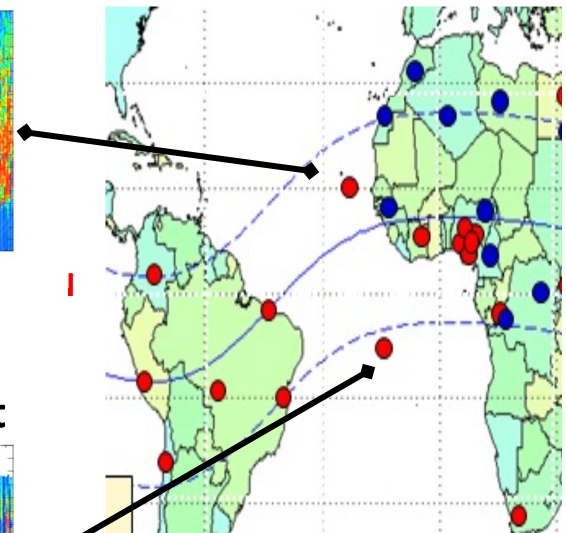
2011

Cape Verde VHF Scint



Ascension Island VHF Scint

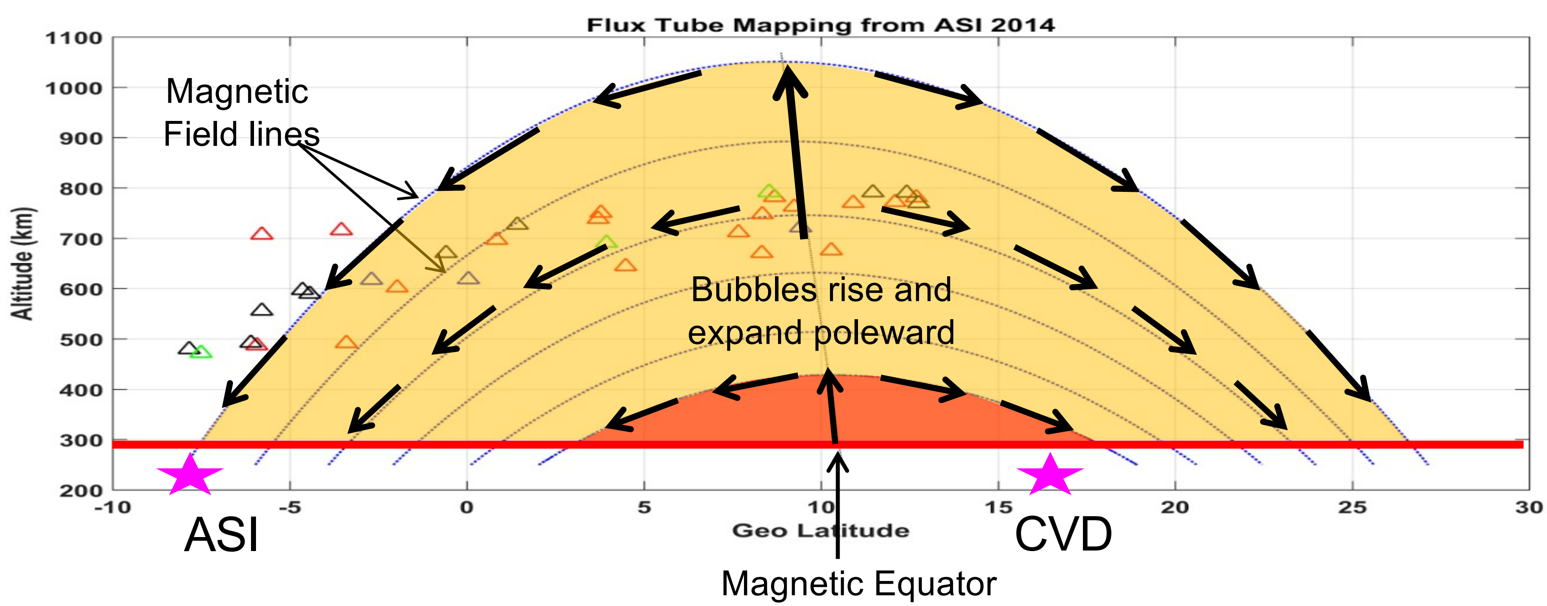




- Ground-based data show that scintillation occurrence at Ascension Island is consistently lower at than Cape Verde, which is closer to the magnetic equator.
- Relative differences are solar cycle dependent; differences are very significant during periods of moderate to low solar flux (see circled period in plot at left).

Mapping Disturbances Along Magnetic Flux Tubes

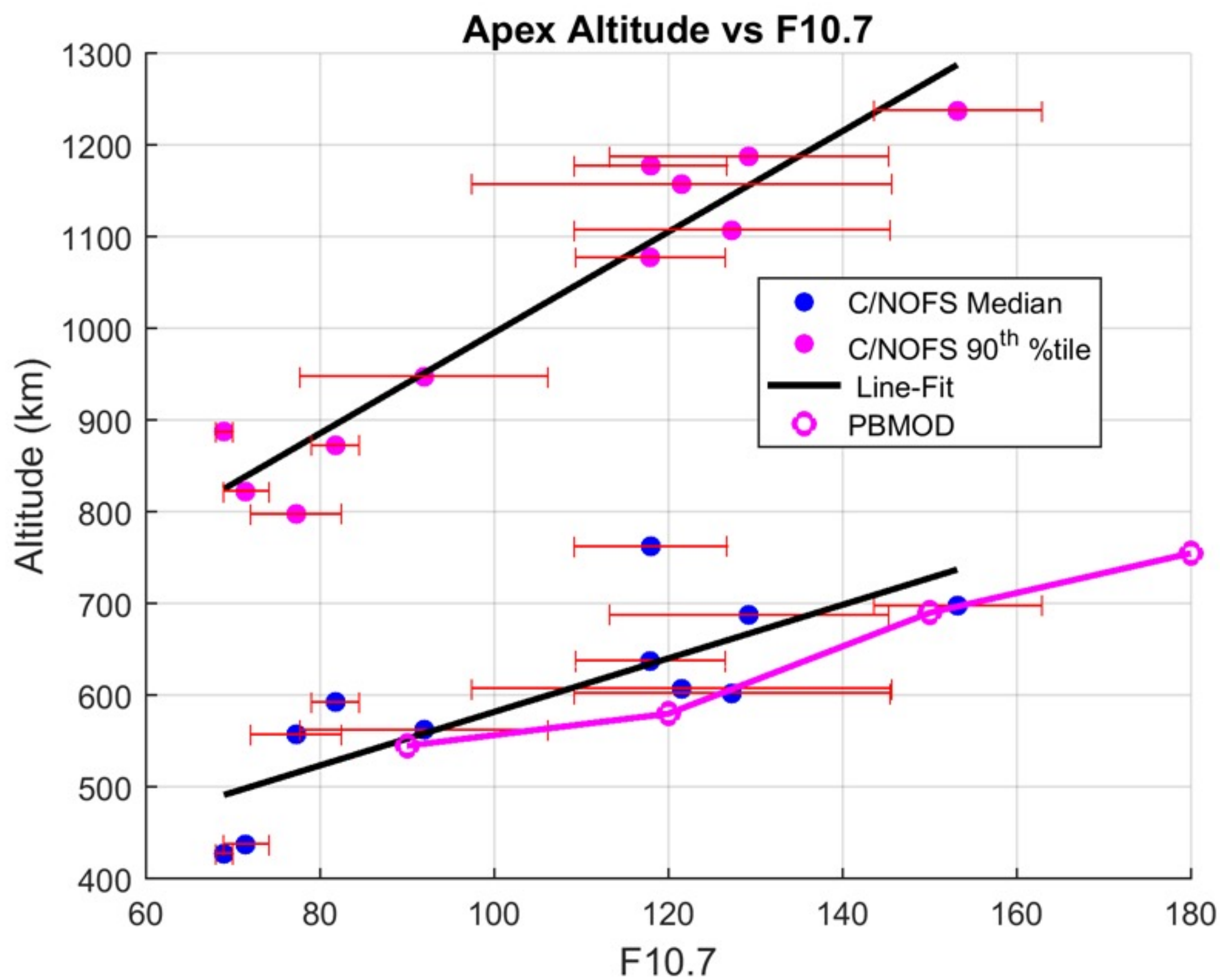
- The bubbles can be considered an electric field structure that maps poleward along the magnetic field lines.
- Thus, the height of the bubbles determines the extent of their expansion along a given magnetic meridian (latitude).
- Bubbles must rise above 1000 km, for example, to reach Ascension Island (ASI) whereas structures reaching just 400 km will reach a low latitude site such as Cape Verde (CVD).



The height of the bubbles depends on solar flux

Peak Bubble Heights: Solar Flux Dependence

- Irregularities observed on the C/NOFS satellite from 2008-14 showed a pronounced increase in occurrence altitude as solar flux increased.
- The results were confirmed with a physics-based self-consistent fluid model calculation (PBMOD).
- The electric fields in the bubble are greater during high solar flux periods due to sharper conductivity gradients.



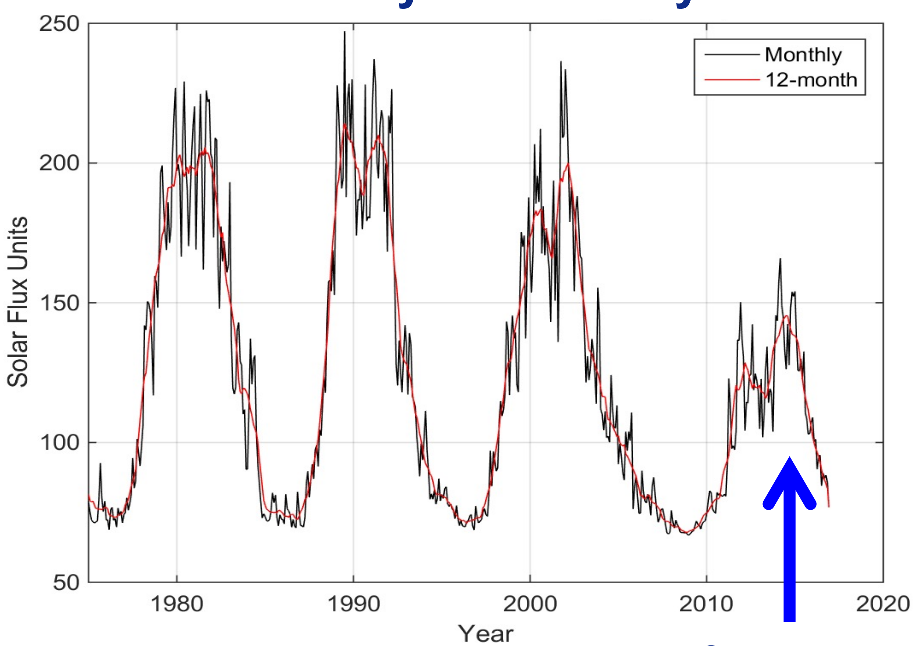
An increase in bubble altitude corresponds to an increase in latitude affected by the irregularities

GPS Positioning Errors from Solar Cycle 24

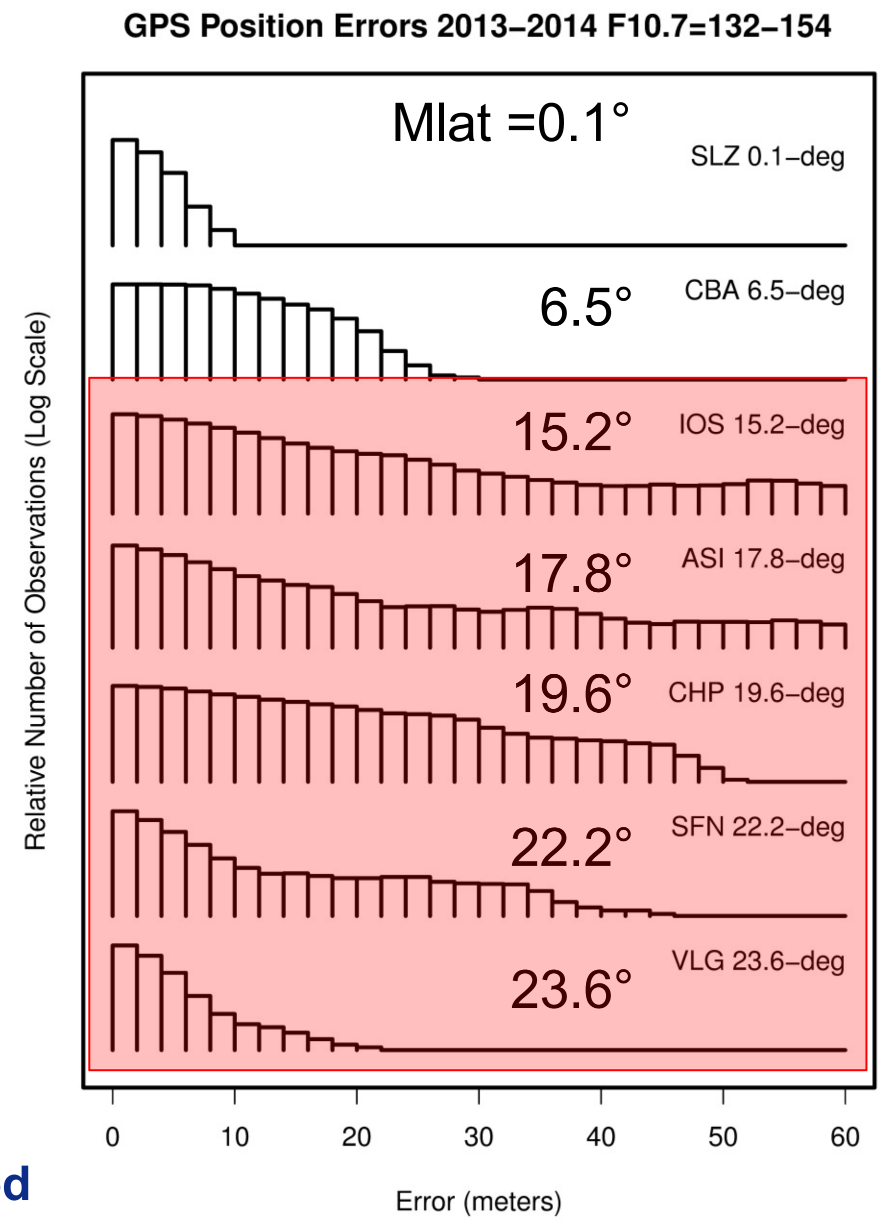
Magnetic Latitude Dependence

- Night time positioning errors in South America 2013-14
- Largest errors occur 15°-20° from magnetic equator
- Moroccan territory extends throughout the transition region

Solar Cycle Intensity



Data Collection Period



Summary

- Ionospheric irregularities are a pervasive problem in the nighttime equatorial ionosphere
- Irregularity strength is modulated by the background density which is, in turn, controlled by the solar flux…the **solar cycle determines scintillation strength**
- Scintillation intensity depends on the amplitude of the integrated density fluctuations near the Fresnel scale along the path and frequency of the radio wave (decreases with increasing frequency)
- Global irregularity knowledge facilitates specification of propagation effects on any system at any time anywhere in the world; at present we are not able to forecast the instabilities that generate irregularities, but we understand their morphology and climatology
- Portions of Morocco may be subject to severe ionospheric scintillation during periods of high solar flux; conversely, its location offers excellent opportunities for observing the ionospheric anomaly and its variability from day-to-day and throughout the solar cycle